FINAL REPORT

Innovative Phase Change Approach for Significant Energy Savings

ESTCP Project EW-201138

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14. ABSTRACT

A hybrid Environmental Control Unit (HECU) technology was demonstrated. The HECU integrated heat exchangers filled with Phase Change Material (PCM) into a facility's air conditioning system. The PCM acts as a thermal battery storing cold energy to supplement the facility's ECU operations reducing operational energy consumption, peak demand, and cost. After extensive pre-demonstration testing at ARA facilities, two methods of integrating PCM into a facility's air conditioning system emerged: 1) PCM-filled coils suspended under ceiling air registers, a simple retrofit, this method targeted continuous PCM use by ensuring the coils were always in the path of air flow. 2) Peak Load Shaving (PLS) using a large PCM-filled coil. This PLS method used PCM module with large thermal storage capacity to absorb heat and maintain room temperature during the peak demand period of the day. The air conditioner then regenerated the PCM during early morning hours, when the air conditioners ran more efficiently and the price of electricity is lower. The ceiling PCM-filled coils demonstration showed a 19% reduction in air conditioning energy use compared to the baseline. While, the PLS demonstration, using storage capacity for 1/3 of the peak period, showed 1.47% energy savings and based on Tyndall AFB electricity pricing reduced the air conditioning energy cost by 6.2%.

15. SUBJECT TERMS

Phase Change Material, PCM, air conditioning, energy savings, peak load shaving.

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List of Acronyms

3D	– Three Dimensional
AAD	– Automatic Airflow Damper
AFB	– Air Force Base
AIRR	– Adjusted Internal Rate of Return
ARA	– Applied Research Associates
BLCC	– Building Life Cycle Cost
BP	– Balance Point
CA	– California
CBP	– Cooling Balance Point
CDD	– Cooling Degree Days
CFM	– Cubic Feet per Minute
DoD	– Department of Defense
ECU	– Environmental Control Unit
FL	– Florida
FPI	– Fins Per Inch
HECU	– Hybrid Environmental Control Unit
HBP	– Heating Balance Point
HDD	– Heating Degree Days
H_r	– Humidity Ratio
HSC	– Heat Storage Capacity
kg	– kilogram
kJ	– kilojoule
kW	– kilowatt
kWh	– kilowatt hour
lb	– Pound
MSDS	– Material Safety Data Sheet
NPT	– National Pipe Thread
PCA	– Principal Component Analysis
PCM	– Phase Change Material
PLS	– Peak Load Shaving
PT18	– PureTemp18, commercial phase change material
SIR	– Savings-to-Investment Ratio
Q18	– QuarTek 18, commercial phase change material
UHMWPE	– Ultra High Molecular Weight Polyethylene
VI	– Virtual Instrument

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The Applied Research Associates (ARA) team members contributed to the final report are: Christopher Church, Donielle Blount, Dr. Sergio Escobar, Alexander Forbes, Desiree Kettell, Robert McDonald, Dr. A. Jensen Newman, Dr. Aly Shaaban, Dr. Abdelfatah Yacout, and Dr. Gong Zhou.

EXECUTIVE SUMMARY

The novel technology developed during this effort is a hybrid Environmental Control Unit (ECU). The Hybrid ECU (HECU) integrates a heat exchanger filled with Phase Change Material (PCM) into a facility's air conditioning system. When installed, the PCM acts as a thermal battery storing cold energy to supplement the facility's ECU operations reducing operational energy consumption, demand, and cost.

PCM absorbs and releases a large amount of latent heat within a narrow temperature range as it undergoes phase change. As the temperature increases above the start point of the melting range, PCM melts and absorbs heat. Similarly, as the temperature drops below the starting point of the solidification range, heat is released as the PCM solidifies.

After extensive pre-demonstration testing at ARA facilities, two methods of integrating PCM into a facility's air conditioning system emerged: 1) PCM-filled coils suspended under ceiling air registers. A simple retrofit, this method targets continuous PCM use by ensuring the coils are always in the path of air flow. 2) Peak Load Shaving (PLS) using a large PCM-filled coil. This method uses PCM module with large thermal storage capacity to absorb heat and maintain room temperature during the peak demand period of the day. The air conditioner then regenerates the PCM during early morning hours, when the air conditioner runs more efficiently and the price of electricity is lower.

When demonstrating the PLS technology, the unit selected could only carry 1/3 of the peak heat load due to manufacturing, cost limitations, and demonstration site space availability. To evaluate this technology against the objectives, the performance results for the demonstrated unit were extrapolated; assuming 3 times the mass of the demonstrated PCM was required to manage the full peak heat load. This extension of the demonstrated technology was compared to the objectives for evaluation.

The success and savings of each application described above was evaluated using the same set of performance objectives. These performance objectives were divided into six quantitative performance objectives and the seventh is a qualitative performance objective.

1. **Reduce Air Conditioning Electric Consumption:** Success criteria – ≥ 30% reduction in cooling energy consumption compared with baseline energy consumption.
    - **Result for PCM Ceiling Coils:** The demonstration showed a 19% reduction in air conditioning energy use compared to the baseline. Achieving greater than 30% reduction in energy consumption requires three changes in the application of the PCM: 1) redesigning the PCM ceiling coils to regenerate in lesser time to save the energy used in regeneration; 2) Use different medium for regeneration than air; and 3) Change the role of PCM ceiling coils from a subservient to the air conditioning unit to be the main source of cooling and the air conditioning unit regenerate the PCM as needed.
    - **Result for Peak Load Shaving PCM Coil:** The demonstration of the PLS coil showed 1.47% energy savings and based on Tyndall AFB electricity pricing this reduced the air conditioning energy cost by 6.2%. Using the bigger capacity PLS coil that covers all of the 6 hours peak demand period can result in reduction of 5.33% in energy use and 20.88% in energy cost. The demonstration did not show significant energy savings due to the PCM in the PLS coil has to be regenerated using the same air conditioning

unit and air as the heat transfer medium. If PCM can be regenerated at night using ambient low temperature air, or ground source cooler water, this application will significantly reduce energy consumption.

2. **Reducing Peak Electrical Demand:** Success criteria – Demonstrate 2 hours of peak demand reduction.
   - **Result for Peak Load Shaving PCM Coil:** During the demonstration, the PLS coil covered the two hours it was designed for.
3. **Provide Comfort Zone Conditions:** Success criteria – Room temperature in the range of 71-73F and relative humidity ≤ 65%.
   - **Result for PCM Ceiling Coils:** During the demonstration, the PCM-filled coils maintained the room temperature and humidity within these criteria.
   - **Result for Peak Load Shaving PCM Coil:** The demonstration showed the PCM can maintain room temperature in the range of 71-73^{o}F during the peak hours. The relative humidity, however, increased from 63% to 78% during the operation. Two factors contributed to this increase: 1) the building is located in a high humidity climate where the building average humidity had been in the range of 55-75% even without the PCM unit, and 2) the PCM had a higher melting point temperature, 64.4^{o}F, than the dew point for the room conditions. At 72^{o}F and 60% relative humidity the air dew point is 52.18^{o}F. To reduce the relative humidity to proper levels, alternative PCM can be chosen with a lower melting temperature than the air dew point to condense the water from the humid air.
4. **Measure Maintenance Frequency:** Success criteria – Maintain maintenance requirement as current system
   - **Result for PCM Ceiling Coils:** After the initial installation, the PCM ceiling coils operated passively and did not require additional maintenance.
   - **Result for Large PCM Coil for Peak Load Shaving:** After the initial installation, the PCM PLS coil operated passively and did not require additional maintenance.
5. **Minimize System Air Pressure Drop:** Success criteria – Maximum of 2% increase in Air Handler Fan energy consumption
   - **Result for PCM Ceiling Coils:** The demonstration showed that after installation of the PCM module, fan energy consumption did not increase and air flow rate did not decrease.
   - **Result for Peak Load Shaving PCM Coil:** The demonstration showed that after installation of the PCM module, fan energy consumption did not increase, and airflow rate only decreased by about 100 CFM (from original air flow rate of 1600 CFM). This did not affect the operation of the air conditioning unit and there is no need to change air handler fan. It should be noted that the drop in the airflow rate due to the installation of the PCM module can be attributed to two factors: 1) pressure drop across the PCM module, and 2) pressure drop due to the installation of the additional duct system. The second factor can be avoided because the PCM is designed to be a drop in unit to the existing duct system. Because of the physical space constrains of the demonstration

site, an extended length of new duct system had to be installed to route the air flow for the demonstration, and therefore the pressure drop of overall system was increased. Without the installation of the new duct system, the air flow rate drop, due to the PCM module, should be less than 100 CFM , 6.25% of the original air flow rate, and has even less impact to the existing air handler system. With the installation of the new duct system, if the original flowrate of 1600 CFM to be maintained, the fan power would increase by approximately 16% to maintain the static pressure at 0.4 inch of water.

6. **Economic Benefits:** Success criteria – < 6 years discounted pay-back period, SIR.

   - **Result for PCM Ceiling Coils:** The current design of the PCM ceiling coils could not meet the 6 years payback period. A redesign focusing on higher energy density storage, quicker PCM regeneration, and reduced manufacturing cost is necessary to approach this target.

   - **Result for Peak Load Shaving PCM Coil:** The demonstration showed that the current design for the PLS coil could not meet the target 6-year payback period. In regions with high fluctuation in peak price and large daily ambient temperature changes such as Sacramento, CA, the current design could achieve a 22 year pay-back period with a product lifespan of 30 years. If night-time air recharging was used, the pay-back period could occur in 14 years. Improvements that will help approach the target payback period include obtaining PCM with higher specific thermal storage, which will reduce the unit footprint and cost.

7. **Ease of Use and Maintenance:** Success criteria – A single field technician able to effectively use and maintain the unit with minimal training

   - **Result for PCM Ceiling Coils:** The PCM ceiling coils can be installed by field technicians with proper training. After the installation, the ceiling coils operated passively and did not require additional adjustments or maintenances.

   - **Result for Peak Load Shaving PCM Coil:** Field technicians with proper training can install The PCM PLS coil. The PLS coil operated passively and did not require additional adjustments or maintenances. Therefore, no additional work by field technician was needed for the PLS coil. A single field technician with ECU training only requires minimal additional training to check and handle the operation of the PLS coil.

The PLS energy cost savings could be much higher, again using Tyndall AFB electricity pricing, the building can save 5.33% in energy use and 20.88% in energy cost if the entire peak period is managed by the PCM unit. Further, the demonstration shows that the energy cost savings could be higher in region with larger fluctuation in peak prices. Using Pacific Gas and Electric (PG&E) pricing for Sacramento California, 30% air conditioning energy cost saving is possible.

Inability to meet energy savings and comfort objectives can be addressed through a change in the operation mode of the integrated PCM coils and the use of a PCM with lower melting point. In the current mode of operation, the air conditioner is the heart of the system, and the PCM unit supplements its operation. A better approach is to make the PCM coils the main system components, where the air conditioner supplements the PCM unit. In this manner, when the room

needs cooling, the thermostat then triggers the air handler fan only, allowing the PCM coils to absorb heat from the room. Once the PCM is fully melted, as indicated by PCM temperature, the condenser unit is activated until the PCM is fully regenerated. Therefore, the PCM provides cooling to the room, and the air conditioner is only used when regeneration is needed. This mode of operation keeps the PCM temperature close to the phase change temperature, allowing the high latent heat capacity of PCM to be better used.

1 INTRODUCTION

The sharp rise in the use of energy has had a debilitating effect on the environment due to CO_2 emissions and economy due to the high cost of energy. In fact, residential and commercial buildings' energy use credited to up to 50% of CO_2 emissions from electric powerplants. Heating, air conditioning, lighting, and information technologies have made our buildings increasingly hungry for energy. Under the Kyoto Protocol, industrialized countries have agreed to curb their CO_2 emissions 75% by 2050. To accomplish this goal, energy consumption has to be reduced by developing energy efficient technologies to maintain the level of activities we currently have. It is estimated that reducing our energy consumption in the US 30% by 2020 would eliminate the need for 1,000 new power plants, a significant reduction in CO_2 emissions and energy cost rate.

1.1 BACKGROUND

Currently, Department of Defence (DoD) spends about $4 billion per year on facility energy consumption and air conditioning equipment are the largest energy consumer in DoD installations. Today, air conditioning equipment is targeted as a major source of potential energy savings that can help in reducing both energy consumption and cost. In an attempt to meet Executive Orders (EOs) requirements, the DOD opted to set thermostats to 78°F (25.6°C) in the cooling season and 68°F (20°C) in the heating season as a means to reduce energy consumption, however does not maintain comfort zone needs. This effort is in response to the Air Force and EOs requirements to achieving energy savings and greenhouse gases reduction, but targets comfort zone limits of room relative humidity and temperature where room temperature is maintained around 72°F (22°C), which is consistent with how most of the existing building stock equipment was designed and is operated, while reducing energy consumption.

A novel approach using Phase Change Materials (PCM), designed to maintain a specified room temperature, can be integrated into the air conditioning system of a building resulting in a hybrid Environment Control Unit (ECU) where PCM module acts as a thermal battery. PCM, with its high latent heat capacities, is designed to absorb and release large amounts of heat within a given, narrow temperature range. As the temperature rises above its melting point, PCM melts as it absorbs heat. As the temperature drops below solidification point, heat is released as the PCM solidifies, and a cooling-heating cycle is regenerated. The results are a more comfortable environment, with fewer temperature peaks and valleys, and a reduction/shift in energy consumption/demand. The reduction and shift of energy demands are critical especially in those States where electrical demand during peak periods can cost upwards of dollars instead of cents a kilowatt.

We demonstrated a Hybrid ECU, in two configurations, which consisted of PCM modules integrated with the air conditioning unit of the demonstration site at Tyndall AFB to evaluate the impact of the PCM on the energy use, demand, and cost. Each PCM unit was designed to use air as the heat transfer medium to maximize the effectiveness of heat transfer from room air to PCM at minimum pressure drop.

Current technology approaches apply PCM to building walls or in slurries for water chillers. The application of PCM in walls, and the future applications in floor tiles, or office furniture is a passive approach which will add higher R-values to the walls and floors. In an experimental effort to study the use of PCM in ceiling applications, Kośny et al [1], using microencapsulated paraffinic PCM, found significantly lower heat fluxes in the PCM wall: peak-hour heat flux was reduced by at least

30% compared with the conventional wall without PCM. In addition, a shift of about 2 h in the peak-hour load was observed in the PCM wall. The PCM microcapsules were between 2 and 20 micrometres in diameter, and their melting point was 78.5°F. Analysis of the temperature profiles in the tested walls showed that the PCM was going through full charging and discharging processes during the 24-h time period, and that the PCM thermally stabilized the core of the wall as a result of its heat storage capacity.

Phase change slurry (PCS) is another technology under development. The slurry is made from either an emulsified PCM in a fluid or micro-encapsulated PCM in a fluid. It is an attractive alternative to chilled water for comfort cooling applications. It improves the heat capacity of water, transferring double the heat/cool thermal load between water chiller and point of use. A water emulsion containing 30wt% paraffin has a heat capacity of 50kJ/kg in the 5 to 11ºC range, double that of water in the same temperature range.

The Hybrid ECU technology uses a PCM with heat capacity of 207 kJ/kg and it is designed to absorb room thermal loads to minimize air conditioning use and to level load demands for air conditioning.

1.2 OBJECTIVE OF THE DEMONSTRATION

The technical approach of the project consists of five goals:

1. Determine demonstration site baseline energy consumption;
2. Develop the air-to-PCM unit;
3. Determine demonstration site performance while retrofitted with the PCM technology; analyse performance data and calculate actual savings;
4. Determine implementation parameters; and
5. Prepare a technology transition plan for DoD wide implementation.

The overarching objective was to demonstrate that Phase Change Material (PCM) in a heat exchanger design and integrated into building ventilation system can result in significant energy savings on DoD Installations while:

a) Maintaining cooled spaces within a comfortable temperature and humidity ranges (71-73ºF, ≤ 65%), and
b) Reducing facility energy consumption and shave peak cooling electric demand

This technology integrates a PCM heat exchanger to current air conditioning technologies. The medium of heat transfer is air, where in the cooling mode warm room air flows through the PCM unit releasing its heat to the PCM and cools down to near the PCM melting temperature. While in the regeneration mode, cold air flows through the PCM unit absorbing the heat stored and dropping the PCM temperature to below its solidification temperature. The demonstration has shown the energy savings and energy cost savings for the HECU technology.

1.3 REGULATORY DRIVERS

The application of the successful hybrid PCM technology will afford the energy managers in the federal government to meet the requirements of the regulatory drivers. Specifically, it will allow them to maintain Federal leadership in sustainability and greenhouse gas emission reductions (EO13693; The Energy Policy Act of 2005). It will also meet the Enhanced Energy Efficiency alluded to in The American Clean Energy Act of 2009. Since new and novel American technologies will maintain America's technological superiority, the hybrid PCM technology will

meet the requirements of the Energy Independence and Security Act of 2007. The drivers which the Hybrid ECU technology addresses are listed below, with a brief description of the sections dealing with the energy demands and efficiency issues; and commercialization of American technologies.

1.3.1 Executive Orders

Executive Order 13693 "Planning for Federal Sustainability in the Next Decade"
The goal of EO 13693 is to maintain Federal leadership in sustainability and greenhouse gas emission reductions.

Section 16 of this EO revokes the following:
Executive Order 13423 of January 24, 2007;
Executive Order 13514 of October 5, 2009;
Presidential Memorandum of December 2, 2011 "Implementation of Energy Savings Projects and Performance-Based Contracting for Energy Savings";
It encourages 1) employing innovative and emerging technologies 2) demand side management and 3) reinforcing the use of energy service companies.

1.3.2 Legislative Mandates

The Energy Policy Act of 2005 Section 902 Goals, states the first goal is "increasing the efficiency of all energy intensive sectors through conservation and improved technologies."

Section 911 Energy Efficiency has an objective of "reducing the cost of energy and making the economy more efficient and competitive" and "improving the energy security of the United States."

The Energy Independence and Security Act of 2007

Section 911 United States Assistance for Developing Countries (a)… "shall support policies and programs" (3) "to promote the use of American-made clean and efficient energy technologies, products, and energy and environmental management services."

The American Clean Energy Act of 2009 was intended "To promote clean energy technology development, enhanced energy efficiency, improved energy security, and energy innovation and workforce development, and for other purposes." A "clean energy technology" refers to a "technology related to the production, use, transmission, storage, control, or conservation of energy that will – (A) reduce the need for additional energy supplies by using existing energy supplies with greater efficiency…"

Section 104 Energy Technology Deployment Goals is to "promote (1) sufficient electric generating capacity using clean energy technologies to meet the energy needs of the United States…"

Section 275 National Energy Efficiency Improvement Goals states "The goals of the United States are- (1) to achieve an improvement in the overall energy productivity of the United States (measured in gross domestic product per unit of energy input) of at least 2.5 percent per year by the year 2012; and (2) to maintain that annual rate of improvement each year through 2030."

1.3.3 Federal Policy

The 2006 Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (MOU) states some goals and objectives are to "reduce the total ownership cost of facilities" and to "improve energy efficiency and water conservation."

1.3.4 DoD Policy

The DoD Strategic Sustainability Performance Plan of 2010

Section I.1 "DoD embraces sustainability as a means of improving mission accomplishment" and in section I.1.A Energy and Reliance on Fossil Fuels under Energy Management in Operations "…reducing the energy demands of our operational forces is a major focus of the Department's efforts to cut energy consumption, and our combat operations will benefit as a result."

The 2010 MOU between the U.S. DoE and the U.S. DoD Concerning Cooperation in a Strategic Partnership to Enhance Energy Security states that, "The DoD aims to speed innovative energy and conservation technologies from laboratories to military end users," and "solving military challenges through innovation has the potential to yield spin-off technologies that benefit the civilian community as well."

1.3.5 Service Policy

The Air Force Energy Plan of 2010 states "The Air Force is the largest consumer of energy in the U.S. federal government…In Fiscal Year (FY) 2008, the Air Force spent approximately $9 billion to fuel aircraft and ground vehicles and provide utility services (primarily electricity and natural gas) to installations." One of the Air Force 2030 Energy End State Goals is that "Research, Development, Test, and Evaluation (RD&TE) has delivered the new cost-effective energy technologies necessary to substantially reduce demand and increase supply".

The Army Energy Security Implementation Strategy (AESIS) of 2009 states that, "In 2008 alone the Army spent over $4.1 billion for fuel and energy." The Army Energy Security Mission is to "make energy a consideration for all Army activities to reduce demand, increase efficiency, seek alternative sources, and create a culture of energy accountability while sustaining or enhancing operational capabilities".

The Naval Energy Strategy of 2009 states that "The Department of Defence alone uses 93 percent of the Federal Government's energy and is the largest single consumer of energy in the United States." To increase tactical energy security within the Department of the Navy, more efficient use of energy is needed for expeditionary applications. "The expeditionary community will work toward lightening the load and reducing the fuel consumption of vehicles, generators, and other equipment."

2 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

This work investigated phase change material's (PCM) ability to deliver energy and cost savings in fixed buildings. PCM is a substance that absorbs/releases substantial thermal energy as it changes phase within a specific temperature range. For example, water is a PCM that absorbs/releases 334 kJ/kg as it melts/freezes at around 32°F. More sophisticated PCM's may change phase over a range of temperatures, and the melting and freezing temperature ranges may not be identical.

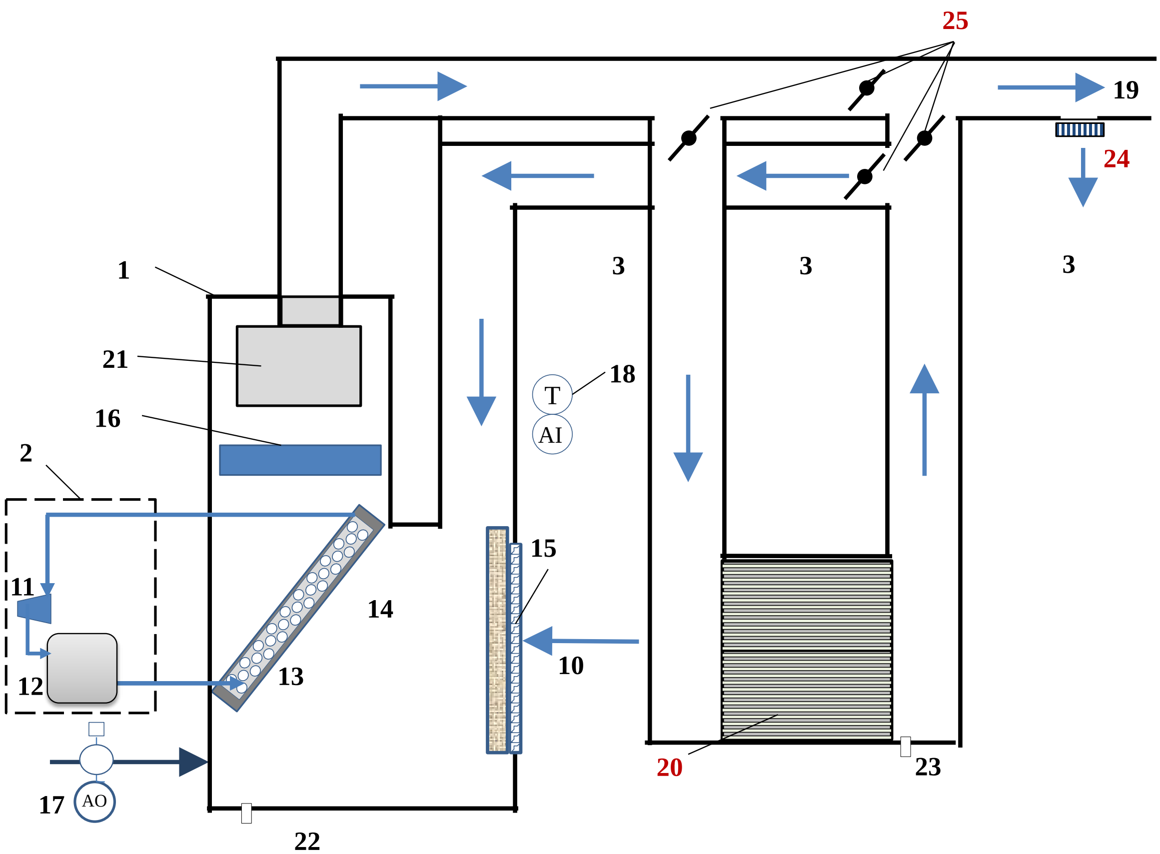
This work's general methodology was to integrate PCM into building's Environmental Control Unit (ECU) systems. PCM would be frozen using the ECU, and then melted later to provide space cooling without using the ECU. This methodology was expected to yield both energy and cost savings. Two distinct technology approaches were taken.

The first approach was to integrate multiple small PCM filled heat exchangers with the ECU air delivery system. These heat exchangers installed under ceiling air registers so cold air passed through them just before entering the conditioned space. These heat exchangers would provide additional cooling at each cooling cycle's end, thereby increasing time between subsequent cooling cycles saving energy.

The second approach was to integrate one large PCM filled heat exchanger with the ECU air delivery system. This heat exchanger was installed just after the ECU system's air handler. This approach sought to shift ECU usage from afternoon (peak hours) to early morning (non-peak hours). Shifting hours in this way leads to energy savings in addition to energy cost savings when variable price plans are employed. These two approaches are henceforth referred to as Ceiling Coils and Peak Load Shaving (PLS).

Both approaches have four main technology components: 1) PCM, 2) Heat Exchanger(s), 3) Controls, and 4) Integration Hardware.

These components integrated as roughly shown in Figure 1. PCM stores thermal energy so that space-cooling may be achieved without using ECU system's condensers. Heat exchanger coils house PCM, and facilitate heat transfer between air and the PCM. This process is critical in both storing and releasing thermal energy from PCM. In the demonstration, controls and hardware are required to modify ECU system operation to account for the inclusion of PCM filled coils. Integration Hardware is all peripheral materials. Demonstration site baseline testing, components' design, components' lab testing, demonstration testing, and evaluation of performance as a whole system of these components comprises the work discussed herein.



1 Air Handler
2 Condensing Unit
3 Room

10	Return Air	18	Thermostat
11	Compressor	19	Room Supply Air
12	Condenser	20	PCM Module
13	Cooling/Heating/Evaporator Coil	21	Air Blower
14	Return Air Filter	22	Air Handler Drain
15	Return Air Grille	23	PCM Module Drain
16	Heating Strip	24	Air Register PCM Units
17	Outside Make-up Air Damper	25	Air Damper

Figure 1: Broad Technology Integration Schematic

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 Technology Development Outline

Figure 2 shows the Ceiling Coils and PLS coil general development process. PCM quantities and properties, and heat exchanger design depended heavily on site-specific characteristics. Therefore, it was necessary to collect site data prior to designing these technologies. These data included

ambient temperature, humidity, solar radiation, and demonstration building performance. Furthermore, since side-by-side testing was not possible, significant site baseline data was also required to determine energy savings from demonstration results.

Once the technology was designed to meet site criteria, it was laboratory tested. Upon satisfactory results, it was transferred to the demonstration site where baseline/shakedown had been conducted. Afterwards, technology was demonstrated to collect data that was then analyzed to determine its impact of energy saving and energy cost savings.

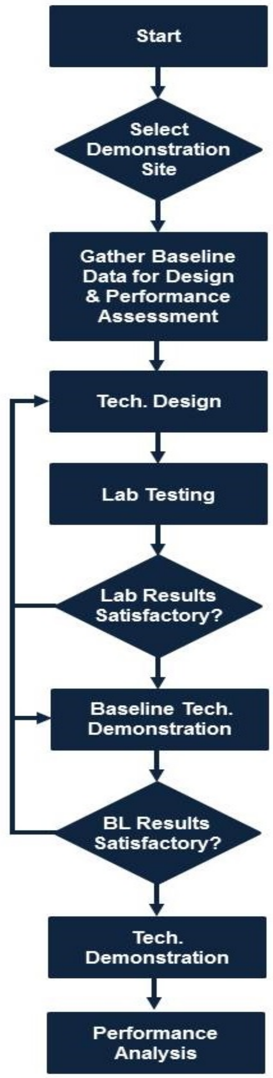


Figure 2: General Process Used To Develop, Demonstrate And Evaluate Technology

2.2.2 Technology Design – PCM

Technology design had some dependence on demonstration site specifics, such as site heat load, which were gathered prior to designing the technology, and is presented in Section 5.2.2.

After conducting a market survey, ARA selected Q18 PCM based on its Heat Storage Capacity (HSC), density, flammability, and availability. This PCM is a eutectic mixture of biodegradable fatty acids. The Material Safety Data Sheet (MSDS-Appendix B) states the material is stable under normal operating conditions and non-hazardous.

Figure 3 shows Q18's HSC as a function of temperature as measured using ASTM Standard C1784–14 [2]. Q18's melting range extends from 14°C (57.2°F) to 22°C (71.60°F) with maximum heat storage at 18°C (64.40F) which designated as the melting point. Its freezing range extends from 19°C (66.20°F) to 13°C (55.40°F) with maximum heat release at 17°C (62.60°F) which designated as the freezing point. The two regions overlap between 14°C (57.2°F) and 18°C (64.40°F).

As its temperature rises above 15°C (59°F), Q18 partially melts until its temperature reaches 22°C (71.60°F). At this temperature, Q18 is completely melted and absorbed a total of 207kJ/kg, Figure 3. As Q18's temperature drops below 19˚C (66.20°F) freezing occurs until 13°C (55.40°F). At this temperature, Q18 is completely solid and released a total of 194 kJ/kg, Figure 3. In the overlap region, both liquid and solid PCM exist. Therefore, as temperature rises and falls within this region, liquid fraction increases and decreases.

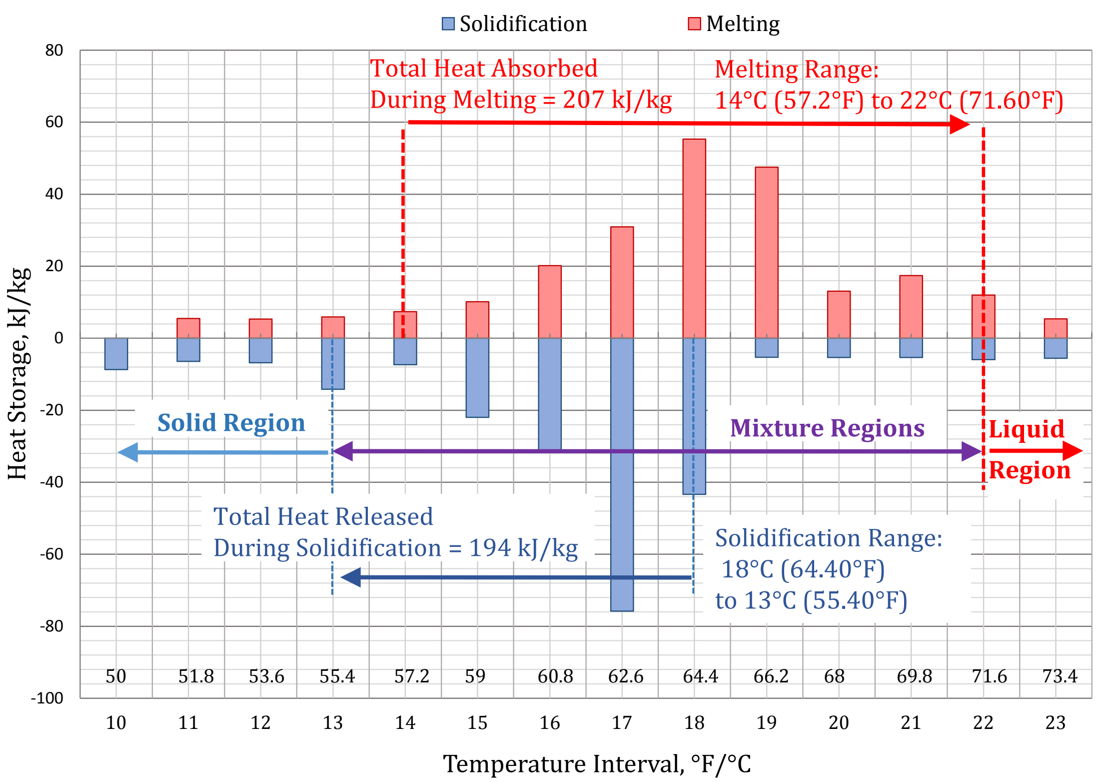


Figure 3: Heat Storage Capacity as a Function of Temperature for Q18

2.2.3 Technology Design – Ceiling Coils

The first step in ceiling coils' design is to determine PCM volume required to manage demonstration building heat loads. To calculate the PCM capacity required for this application, the baseline data (e.g. Figure 14) from the demonstration site was studied on the hottest days available.

For every cycle during the day, heat infiltration was calculated while the ECU was off. The average heat infiltration while the ECU was off was 2,273 kJ with a maximum at 3,233 kJ and a standard deviation of 338 kJ.

To account for possible higher building thermal loads, for example, doors left open or exhaust fans left on, 6,000 kJ was used as the target PCM capacity. Divided between 11 coils (see Figure 12), each ceiling coil required 550 kJ of PCM capacity. Q18 PCM has a latent heat capacity of 175 kJ/kg so each ceiling coil had to contain 3.14kg (6.91 lbs) of PCM.

Heat transfer rates from air to PCM must be as high as possible to effective use of PCM. Off-the-shelf water coils presented an excellent opportunity to test PCM in very efficient heat exchangers without investing heavily in custom prototypes. As copper tubing in the water coils contains the PCM, these tubes' diameter affects heat transfer surface area and phase change rates. Two PCM filled water coil types were developed in relation to the ceiling coils: a 36" × 21" coil for lab testing, and eleven 24" × 24" coils, Figure 4, for installation as ceiling coils in the demonstration building. 24" × 24" coils required 4-tube rows to hold the 3.1kg of Q18 needed to reach 550kJ. Fin spacing was chosen at 10 fins per inch, which performed well in all coil tests.

Figure 4: One of 11 Ceiling Coils Suspended Under Ceiling Air Registers

2.2.4 Technology Design – Peak Load Shaving

To determine required PLS PCM volume, the demonstration buildings' peak-hour heat load had to be determined. This was found to be 85,500 kJ by averaging total heat infiltration during peak hours over many days from data given in Figure 14. Based on Q18's HSC, this required 540 L, but the largest water coil a manufacturer would agree to make was only 180 L. This equates to 28,500 kJ or about one third of the required storage. It was decided that the best approach was to conduct the study using the commercially available water coil, and provide estimates of a larger water coil's performance based on demonstration results. Diversified Heat Transfer manufactured the 180 L coil. It had a face area of 48" x 48", 32 rows of 5/8" diameter .020" wall thickness copper tubing, and 8 fins per inch, Figure 5.


Figure 5: PLS PCM-Filled Coil Prior To Installation At The Demonstration Site

2.2.5 Lab Testing – PCM

Since the proposed technology used a large amount of PCM in a confined space, PCM leakage, evaporation, and fire hazards were of principal concern. At the time of testing, Q18 was not available due to unforeseen manufacturer shortages and later was obtained and used in the demonstration. However, 5 very similar PCMs: PT18, PT23, Q20, Q23, and Q20FR (Fire Retardant) were tested.

Leakage potential was determined at three temperature settings higher than the PCMs melting temperatures: 22.22°C (72°F), 35.56°C (96°F) and 48.89°C (120°F). Each PCM filled a 24” high aluminum tube, and then placed inside temperature-controlled box, Figure 6. Leakage was simulated with a 1/16” diameter hole near the bottom. Time for 25 ml increments of PCM to leak into a beaker was recorded up to 225ml. Each test was performed 3 times for 45 trials total. Time required to leak 225mL was averaged over test numbers and PCM types for each temperature, Table 1.

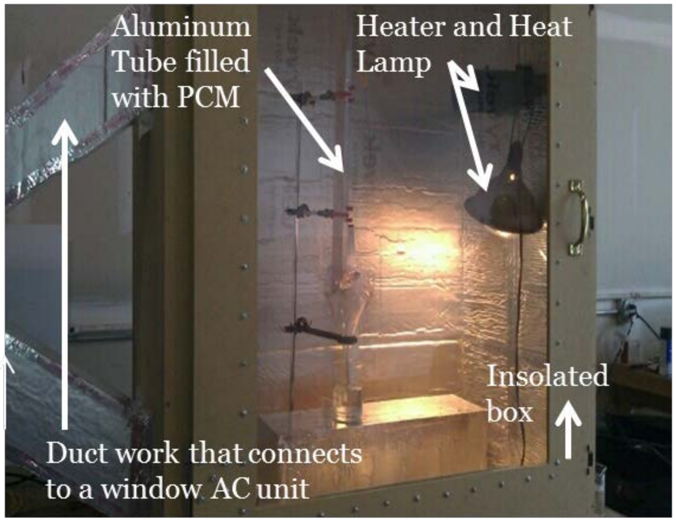


Figure 6: PCM Leakage Test Setup

Table 1: Leak Times Averaged Over Test Numbers

Test Temperature °C (°F)	225 mL Leak Time (Seconds)
22.22 (72)	72
35.56 (96)	69
48.89 (120)	67

Fire hazard properties including surface tension, density, viscosity, flash point, evaporation rate, and auto-ignition were measured for the 5 PCMs using industry standard tests and equipment (Table 2). Surface Tension was measured using a Kruss model K10ST Tensiometer and a platinum Wilhelmy plate. Density was measured using both a gravimetric analysis and an electronic densitometer (Mettler Toldeo Densito 30PX). Viscosity was tested using ASTM D445-11a "Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids and Calculation of Dynamic Viscosity" using a 100ml Canon-Fenske Routine viscometer. Evaporation Rate was measured using Netzsch STA409PC TGA/DSC operated in DSC mode. Hot-flame Auto-Ignition was measured using ASTM E-659 "Standard Test Method for Auto-ignition Temperature of Liquid Chemicals". Flash Point was measured using Procedure A of ASTM-D93-10A "Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester".

Test results, Table 2, indicate that hot-flame auto-ignition and flash point are high enough that no fire hazard risk exists. Also, evaporation rate is so low that no potential risk exists of spreading the PCM into the conditioned space if any leakage occurred.

Table 2: Measured PCM Fire Hazard Properties

		Phase Change Material Tested				
Type of Test	Units	PT18 Liquid	Q20 Liquid	Q20FR Liquid	Q20FR Gel	Q20 Gel
Density	g/cm^3	0.8639	0.8314	0.8314	0.872	0.841
Dynamic Viscosity	Poise (calculated)	0.04012	0.1944	0.1947	not measured	not measured
Surface Tension	mN/m	29.5	29.2	29.2	not measured	not measured
Evaporation Rate	$g/s.m^2$ (mass loss rate)	0.00101	0.00083	0.00059	0.00251	0.00079
Hot-flame Auto-Ignition	Degrees Fahrenheit	642.2	494.6	500	505.4	507.2
Flash Point	Degrees Fahrenheit	302.3	275.1	276.5	not measured	269.2

2.2.6 Lab Testing – Ceiling Coils

Since demonstration building duct branches out to 11 registers, each register only receives a portion, 136 CFM on average, of the full airflow rate. To test how Q18 PCM would perform with low flow rates, the 36” × 21” water coil was tested using 130CFM. Figure 7 shows resulting PCM and air temperatures when air was supplied at about 52°F and 72°F.

Freezing (52°F supply air) took approximately 16 minutes, and melting (72°F supply air) took about 40 minutes. These times fit within condenser unit operation time ranges on a warm day (5-20 minutes).

Since the demonstration building’s registers measured 24” x 24”, it was expected that PCM would change phase faster than observed in the 36” x 21” coil at flow rates close to 130CFM. This is because the air velocity would be higher, enhancing convective heat transfer. With a freezing times less than 15 minutes, 24” x 24” coils with 3/8” tubing were expected to be a good fit with the demonstration site ECU system.

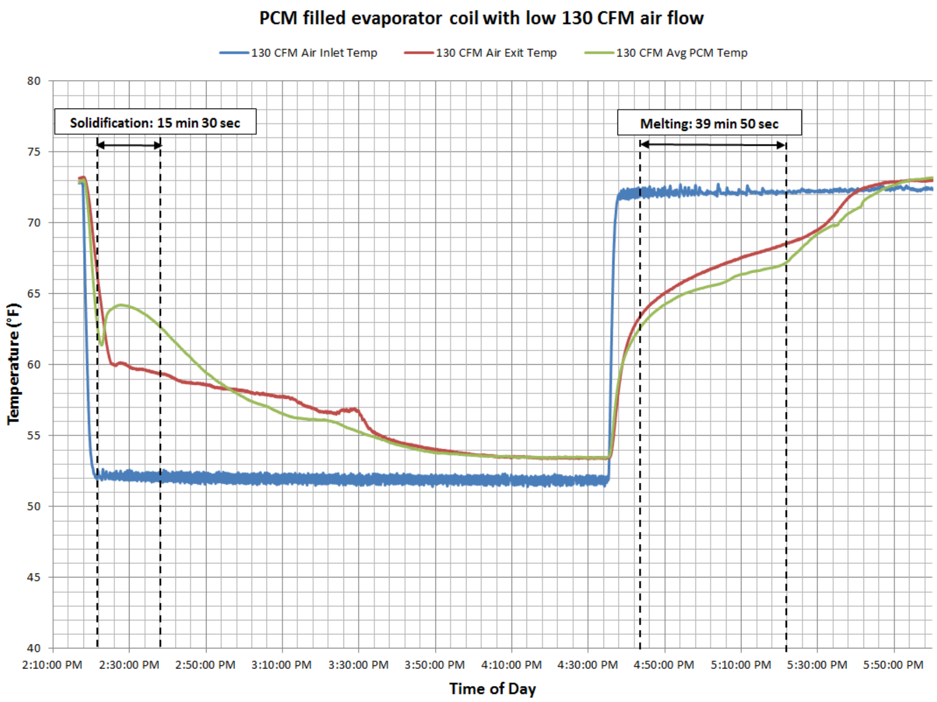


Figure 7: Laboratory Closed Loop Test Showing Solidification and Melting of PCM in the 36”x21” Water Coil at 130 CFM

2.2.7 Laboratory Testing – Peak Load Shaving Coil

The PLS coil was tested in a building and a setup similar to those used in the demonstration site to verify heat transfer rates and storage capacity. As shown in Figure 1, four air dampers controlled airflow. In one setting air flowed through the PLS coil to freeze PCM or cool the room. The second setting bypassed PCM allowing the ECU to cool the room. Two methods were tested for regenerating the PCM in the PLS coil: Intermittent and Dedicated.

Intermittent Regeneration Method

In this charging method, PCM received cold air bursts every time the ECU condenser unit operated; there is no dedicated regeneration period. If successful, this method would be preferable because of its simplistic hardware and controls. During laboratory testing, the peak load shaving operation followed three steps:

1. Normal ECU operation + PCM freezing until 1:00 PM.
2. Continuous cooling with PCM from 1:00 PM until PCM cannot condition the room effectively
3. Normal ECU + PCM freezing operation for the rest of the day

During step 1, the air handler fan cycled with the condenser unit. The PCM gradually froze throughout the day as it received cold bursts of air from the ECU (steps 1 and 3 above). At 1:00 PM, when building heat loads were high, the fan was forced on, and the frozen PCM cooled the room (step 2). A LabView program monitored room cooling. When the PLS coil was no longer able to provide cooling, control was returned to the thermostat and the ECU operated again. Figure 8 shows condenser unit power (light green) air handler power (turquoise), room temperature

(orange), and average PCM temperature in the first tube row (green) while last tube rows (red) during this charging method's testing.

From 12:00 AM to about 8:20 AM, PCM temperature in the first tube row fluctuated between 57°F and 60°F as the condenser unit came on and off. After this period, the condenser unit engaged more frequently, and PCM temperature in the first tube row trended downward. PCM in the first tube row was frozen before peak load shaving started at 1:00 PM, and fully melted at about 2:40 PM. During this time period, PCM temperature increased from 53°F to 73°F at different rates depending on sensible and latent heat absorbed at each temperature. The PCM temperature, in the last tube row stayed almost steady in the melting zone all day except for a brief period around 1:00PM. This was most likely because intermittent regeneration was insufficient to fully freeze the PCM in the last tube row prior to peak load shaving.

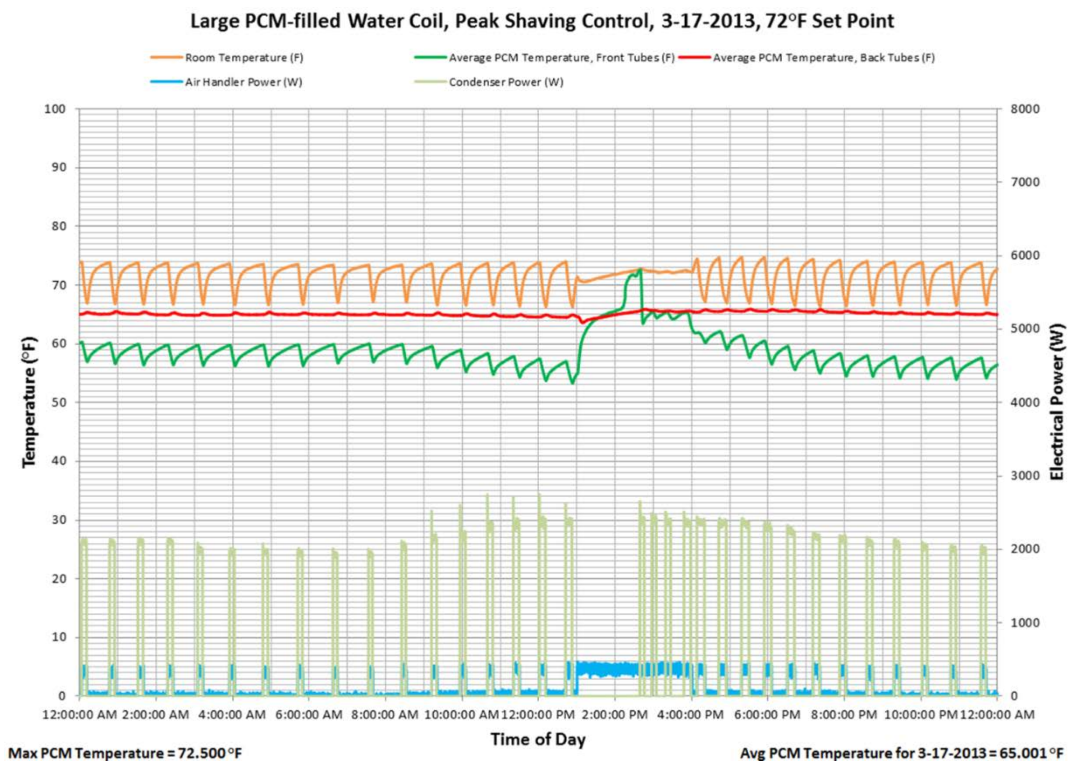


Figure 8: Laboratory Peak Load Shaving Testing – Intermittent Charging Method

Dedicated Regeneration Method

To ensure all PCM was fully frozen, a dedicated regeneration period was used in the morning where the ECU supplied cold air to the PLS coil in a closed loop. When the PCM was not being frozen or used to cool the room, it was bypassed. The control scheme for test the dedicated charging method was as follows:

1. Normal ECU operation until 5:00 AM; PLS coil is bypassed.
2. PCM frozen in a closed loop from 5:00 AM until fully solidified. PCM is considered fully solidified when temperature in the last tube row ≤ 60°F.

3. Normal ECU operation until 1:00 PM; PLS coil is bypassed.
4. PLS coil cools the room from 1:00 PM until it is no longer capable of cooling the room, thermostat triggers the ECU to start cooling the room.
5. Normal ECU operation for the rest of the day; PLS coil is bypassed.

Figure 9 shows condenser unit power (light green), air handler power (turquoise), room temperature (orange), and average PCM temperature in the first (green) and last (red) tube rows during this regeneration method's testing.

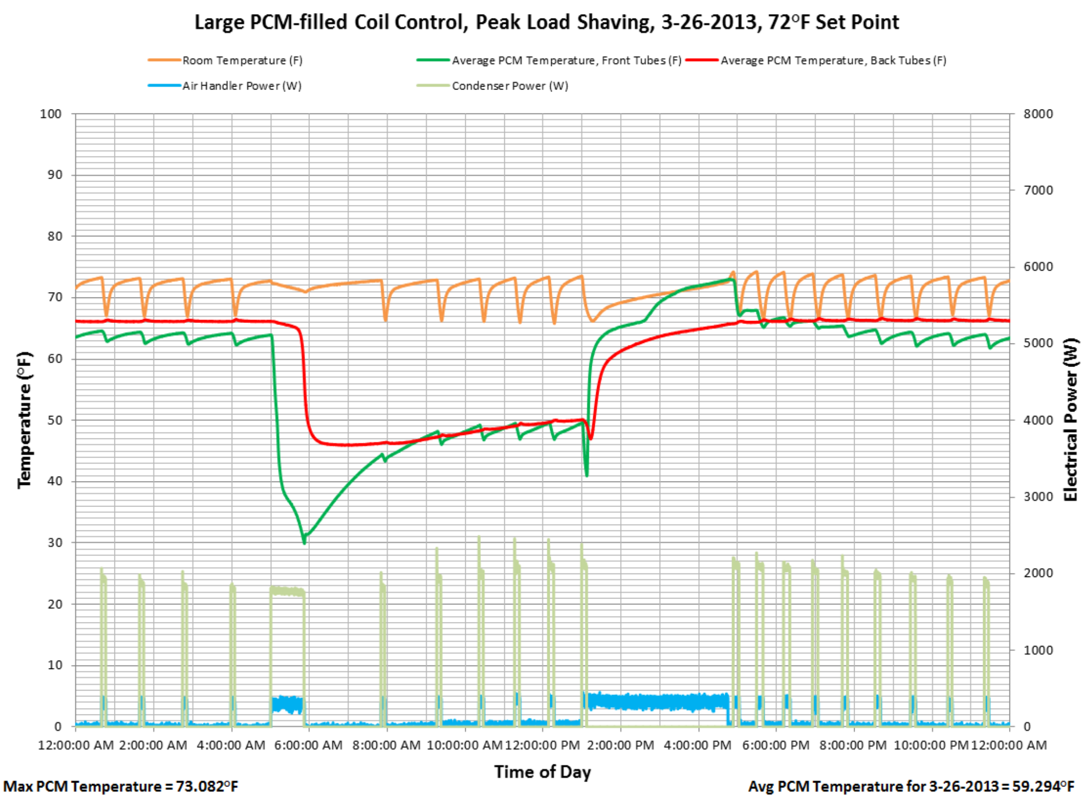


Figure 9: Laboratory Peak Load Shaving Testing – Dedicated Charging Method

In the data presented, freezing completed around 5:50 AM. The PCM coil then sat idle until 1:00 PM when the fan was forced on until room temperatures became higher than the set point. This occurred around 5:00 PM for the presented data. At this point, control was returned to the thermostat.

Figure 9 shows the PLS coil conditioned the room for 4 hours and only required 50 minutes to freeze. Further, since a large portion of air conditioning work was transferred to the morning, it operated at a lower wattage. Confident the PLS coil's ability to shift air conditioning operation from peak hours to off peak hours, the PLS coil was installed in the demonstration building and operated using this regeneration method.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Alternative PCM Technologies for Building Energy Savings

Current approaches to using PCM for building energy savings fall into two categories: Integration with building walls and use as slurries in water chillers. Commercially available products for building walls and ceilings include ThermaMATS^{TM} by Phase Change Energy Solutions (PCES) of Asheboro, NC, and ThermalCORE^{TM} by National Gypsum of Charlotte, NC.

ThermaMATS^{TM} [3] are flexible mats containing pouches filled with PCM. They are installed in walls and ceilings between the drywall and insulation to assist in maintaining a room temperature until the PCM has completely changed phase. ThermaMat, developed by Phase Change Energy Solution Inc., was numerically simulated and experimentally tested by Muruganantham [4]. The results of the research showed the additional layer of PCM can contribute up to 30% savings of cooling energy.

ThermalCORE^{TM} [5] is a gypsum wallboard impregnated with Micronal^{TM} PCM developed by BASF. According to National Gypsum, this PCM is a paraffin wax that melts at 23°C (73°F) and has a latent heat capacity of 22 Btu/ft^2. By comparison, ThermaMATS^{TM} have almost eight times that latent heat capacity with 186 Btu/ft^2.

In phase change slurries (PCS), emulsified or micro-encapsulated PCM is placed in a fluid. One major use for this technology is chilled water for comfort cooling, where the PCM improves the heat capacity of water allowing it to transfer more heating/cooling load between the water chiller and point of use.

2.3.2 Current Approach Advantages

Building wall PCM approaches to building energy savings require remodeling efforts. During these efforts, loss of building use was always guaranteed. On the other hand, a facility can be easily retrofitted by both the Ceiling Coil and PLS coil technologies without severe remodeling or building closures. Using ThermalCORE^{TM} or ThermaMATS^{TM} will require a major remodeling of the facility. Using PCS requires increased pumping power because PCM addition increases fluid viscosity. This limits PCM quantities and adversely affects energy savings. Neither of the ceiling coils and PLS coil approaches suffers from these drawbacks.

2.3.3 Current Approach Disadvantages Noted During Demonstration

Ceiling Coils

Dependence of PCM regeneration on the ECU cold supply air caused the PCM to stay in the mixture region all day, although phase changes had occurred, staying in the mixture region limited the benefit of the full use of the PCM latent heat.

Dependence of PCM regeneration on ambient temperature can also cause suboptimal PCM use on hot days: the condenser unit must run frequently to cool the room that can cause the PCM to change phase between condenser unit cycles however at much lower latent heat exchange with the room.

Low register flow rates do not deliver the heat transfer required to fully melt and freeze the ceiling coils each cycle.

Peak Load Shaving

Dependence of PCM regeneration on the ECU cold supply air resulted in a longer regeneration time and a consequence more energy use which led to low energy saving and energy cost savings. The longer regeneration time was due to the poor heat transfer properties of air. Next generation PLS coil should include a better regeneration approach.

The PLS coil was selected to cover only 2 out of the 6 hours peak load period, due to the size of available water coils and demonstration site available space. Next generation PLS coil should take advantage of PCMs with much higher specific latent heat and compact heat exchanger manufacturing technologies.

3 PERFORMANCE OBJECTIVES

To quantify the energy savings from the proposed PCM technology and achieve the projected goals, a set of performance objectives are used. These performance objectives are divided into six quantitative and one qualitative performance objectives. They include: 1) Reduce Facility Air Conditioning Electric Consumption; 2) Reducing Peak Electric Demand; 3) Provide Comfort Zone Conditions; 4) Measure Maintenance Frequency; 5) Minimize System Air Pressure Drop; and 6) Economic Benefits, while the qualitative Performance Objective for this demonstration is 7) Ease of Use and Maintenance. Achieving these objectives will allow us to calculate actual operational performances including energy and maintenance savings, operational requirements, and investment cost and payback period.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

To quantify the energy savings from the proposed PCM technology and achieve the projected goals, a set of performance objectives were developed. Two PCM technologies were demonstrated in this effort: PCM-filled coils placed under ceiling registers, and a large PCM coil for peak load shaving. These performance objectives and results for both technologies are divided into six quantitative performance objectives and one qualitative performance objective, which are summarized in Table 3.

Table 3: Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results (Ceiling Coils)	Results (Peak Load Shaving)
Quantitative Performance Objectives					
Reduce Facility Air Conditioning Electric Consumption.	Facility's electric usage profile (kWh).	Total energy consumed (kWh), energy consumed in compressor and fans; room temperature and humidity, ambient temperature, and solar incidence profiles.	≥30% reduction in cooling energy consumption compared with baseline cooling energy consumption.	Up to 19% cooling Energy Savings.	Up to 6.2% energy cost saving and 1.47% energy savings.
Reducing Peak Electric Demand.	Facility's electric usage profile (kWh) during peak demand period.	Total energy consumed (kWh), energy consumed in compressor and fans; room temperature and humidity, ambient temperature, and solar incidence	Show 2 hours coverage of the peak demand period with condenser unit off.	N/A	Demonstrated 2 hours of peak demand reduction. To cover the entire 6 hours, three times of the PCM is needed.

Performance Objective	Metric	Data Requirements	Success Criteria	Results (Ceiling Coils)	Results (Peak Load Shaving)
		profiles during peak periods.			
Provide Comfort Zone Conditions	Maintain room temperature and relative humidity steady and comfortable.	Room relative humidity and temperature measurements profile, Feedback from Occupants.	Room temperature in the range of 71-73F and relative humidity ≤ 65% ASHRAE Standards 62.1-2013.	Maintain both temperature and humidity in the range of 70-73F. Relative humidity also stayed ≤ 65%	Maintained room temperature in the range of 70-73F. Relative humidity increased markedly (from 55% to 75%) due to high PCM melting point
Measure Maintenance Frequency	Number of maintenance visits required.	Maintenance data from log in folder.	Maintain maintenance requirement as current system	No additional maintenance requirements	No additional maintenance requirements
Minimize System Air Pressure Drop	Pressure drop measurements in each system component (psi) and Air Handler fan power consumption (kWhr).	Air Flow Rate and Pressures, Air Handler Fan Power.	Maximum of 2% increase in Air Handler Fan energy consumption	No increase in fan energy. Airflow rate drop slightly (100 CFM) 6% no additional fan power needed.	No increase in fan energy. Airflow rate drop 6% (100 CFM) no additional fan power needed.
Economic Benefits	Discounted Simple Payback, Savings-to-Investment ratio.	Unit cost, labor cost, maintenance costs, energy savings.	< 6 years payback period.	19.4% Energy Savings, SIR=0.12	20% energy cost saving, SIR=0.2 (Demonstration Site – Tyndall AFB, FL) SIR=1.81 (Sacramento, CA Case)
Qualitative Performance Objectives					
Ease of use and Maintenance	Ability of a technician-level individual to use and maintain the technology.	Feedback from technician on usability and maintainability and time required to use.	A single field technician able to effectively use and maintain the unit with minimal training.	Passive operation and required no additional operation, maintenance or technicians.	Passive operation and required no additional operation, maintenance or technicians.

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS AND RESULTS

1. **Reduce Air Conditioning Electric Consumption** (This objective was partially met)

   - **Purpose:** To determine the actual reduction in energy consumption attributed to the PCM module. Measurements at the test site with the technology in place will be compared to the baseline period.
   - **Metric:** To quantify energy reduction, the air conditioning equipment energy usage (kWh) will be measured.
   - **Data:** Power demands for the air handler, the condensing unit, and the total building in kW measurement with time to calculate energy consumption in kWh.
   - **Analytical Methodology:** Direct comparison between baseline and demonstration data would yield false conclusions due to weather changes. Use the weather normalization statistical method outlined by Avina [6] will result in an accurate statistical approach to determine the actual energy savings or losses for a retrofit by taking into account the weather changes from the year baseline was measured to the year a new technology is used.
   - **Success Criteria:** A minimum of a 30% reduction in cooling energy consumption.
   - **Result for PCM-filled Ceiling Coils:** The demonstration showed a 19% reduction in air conditioning energy use compared to the baseline. Achieving greater than 30% reduction in energy consumption requires three changes in the application of the PCM: 1) redesigning the PCM ceiling coils to regenerate in lesser time to save the energy used in regeneration; 2) Use different medium for regeneration than air; and 3) Change the role of PCM ceiling coils from a subservient to the air conditioning unit to be the main source of cooling and the air conditioning unit regenerate the PCM as needed.
   - **Result for Peak Load Shaving PCM Coil:** The demonstration of the PLS coil showed 1.47% energy savings and based on Tyndall AFB electricity pricing this reduced the air conditioning energy cost by 6.2%. Using the bigger capacity PLS coil that covers all of the 6 hours peak demand period can result in reduction of 5.33% in energy use and 20.88% in energy cost. The demonstration did not show significant energy savings due to the PCM in the PLS coil has to be regenerated using the same air conditioning unit and air as the heat transfer medium. If PCM can be regenerated at night using ambient low temperature air, or ground source cooler water, this application will significantly reduce energy consumption.

2. **Reducing Peak Electric Demand** (This objective was met)

   - **Purpose:** Reduce peak load electric demands.
   - **Metric:** Facility’s electric usage profile (kWh) during peak load period.
   - **Data:** Total energy consumed (kWh), energy consumed in compressor and fans during peak periods.
   - **Analytical Methodology:** Direct energy use observation during peak demand periods.
   - **Success Criteria:** Complete coverage of 2 hours of the peak demand period with condenser unit off.

- **Result for PCM-filled Ceiling Coils**: N/A
- **Result for Peak Load Shaving PCM Coil:** During the demonstration, the PLS coil covered the two hours it was designed for.

3. **Provide Comfort Zone Conditions** (This objective was met for the PCM-filled Coils Placed Under Ceiling Registers, but it was not met for the peak load shaving demonstration)

- **Purpose:** Maintain a building comfort zone temperature of 72°F and relative humidity less than 65% [ASHRAE 62.1-2013] during baseline and technology demonstration.
- **Metric:** Temperature in °F and relative humidity in % will be used to determine whether or not comfort zone conditions are met. Both during baseline and demonstration testing, a comfort level feedback log was implemented; Appendix D. Feedback from occupants is encouraged but voluntary. For regular occupants feedback is recommended once a week. Comfort level is rated on a scale from 1 through 5. The highest comfort level is a 5 and the lowest comfort level is a 1. Occupants leaving feedback record the date and time, comfort level rating, and any comments they wish to include. Although comfort levels are variable due to individual preferences, this feedback log will be a good indication of whether comfort zone conditions improved after the technology was in place.
- **Data:** Measurements from thermocouples and humidity sensors throughout the building will be used to evaluate whether or not the building stays within the comfort zone. Room conditions are measured at different location to determine average temperature and relative humidity.
- **Analytical Methodology:** Statistical analysis will be used to determine the percentage of time the room stays within the comfort zone conditions with the technology in place compared to the baseline year. From the results of the comfort level feedback log, statistical analysis will be performed to determine the mean, median, and mode of occupant responses. To account for individual preferences, the range and standard deviation of responses will be analyzed as well.
- **Success Criteria:** Room temperature maintained in the range of 71-73°F with the relative humidity maintained below 65%.
- **Result for PCM-filled Ceiling Coils:** During the demonstration, the PCM-filled ceiling coils maintained the room temperature and humidity within these criteria. No feedback was provided by the demonstration building users.
- **Result for Peak Load Shaving PCM Coil:** The demonstration showed the PCM can maintain room temperature in the range of 71-73^{o}F during the peak hours. The relative humidity, however, increased from 63% to 78% during the operation. Two factors contributed to this increase: 1) the building is located in a high humidity climate where the building average humidity had been in the range of 55-75% even without the PCM unit, and 2) the PCM had a higher melting point temperature, 64.4^{o}F, than the dew point for the room conditions. At 72^{o}F and 60% relative humidity the air dew point is 52.18^{o}F. To reduce the relative humidity to proper levels, alternative PCM can be

chosen with a lower melting temperature than the air dew point to condense the water from the humid air. No feedback was provided by the demonstration building users.

4. **Measure Maintenance Frequency** (This objective was successfully met)
   - **Purpose:** Determine maintenance requirement for the new technology.
   - **Metric:** The number of maintenance visits will be used for evaluation. The ECU system maintenance at Tyndall AFB follows a Recurring Work Program (RWP). Air handler units receive quarterly maintenance and condensing units are on a yearly schedule. Records are kept in the mechanical room of the demonstration site for our evaluation.
   - **Data:** Maintenance data will be collected from the maintenance log. Data include number of maintenance visits, type and nature of problem, time taken to diagnose and correct the problem, and cost.
   - **Analytical Methodology:** Statistical analysis will be conducted on maintenance data.
   - **Success Criteria:** This criterion is successfully met if no additional maintenance is needed beyond what the current system requires.
   - **Result for PCM-filled Ceiling Coils:** After the initial installation, the PCM operated passively and did not require additional maintenance. No feedback was provided by building maintenance staff, pointing to no maintenance issues occurred.
   - **Result for Peak Load Shaving PCM Coil:** After the initial installation, the PCM PLS coil operated passively and did not require additional maintenance. No feedback was provided by building maintenance staff, pointing to no maintenance issues occurred.
5. **Minimize System Air Pressure Drop** (This objective was successfully met)
   - **Purpose:** Depending on the pressure drop across the PCM system, a larger fan may be required. This Performance Objective was set to minimize the pressure drop and minimize the cost of putting in a fan rated for higher CFM. The pressure drop will be minimized in two ways: 1) Reducing the pressure drop across the PCM module 2) Reducing the pressure drop in the ducting required to install the PCM module.
   - **Metric:** Pressure (psi) will be used to evaluate pressure drop due to the insertion of the PCM module into the ECU system.
   - **Data:** Pressure transducers immediately upstream and downstream of the PCM modules will measure the pressure drop across each module. Total system pressure drop will be measured by pressure transducers located at the entrance and exit to the duct supporting the PCM modules.
   - **Analytical Methodology:** This is a direct pressure measurement.
   - **Success Criteria:** Maximum of 2% increase in Air Handler Fan energy consumption.
   - **Result for PCM-filled Ceiling Coils:** The demonstration showed that after installation of the PCM module, fan energy consumption did not increase and air flow rate did not decrease.

- **Result for Peak Load Shaving PCM Coil:** The demonstration showed that after installation of the PCM module, fan energy consumption did not increase, and airflow rate only decreased by about 100 CFM (from original air flow rate of 1600 CFM). This did not affect the operation of the air conditioning unit and there is no need to change air handler fan. It should be noted that the drop in the airflow rate due to the installation of the PCM module can be attributed to two factors: 1) pressure drop across the PCM module, and 2) pressure drop due to the installation of the additional duct system. The second factor can be avoided because the PCM is designed to be a drop in unit to the existing duct system. Because of the physical space constrains of the demonstration site, an extended length of new duct system had to be installed to route the air flow for the demonstration, and therefore the pressure drop of overall system was increased. Without the installation of the new duct system, the air flow rate drop, due to the PCM module, should be less than 100 CFM , 6.25% of the original air flow rate, and has even less impact to the existing air handler system. With the installation of the new duct system, if the original flowrate of 1600 CFM to be maintained, the fan power would increase by approximately 16% to maintain the static pressure at 0.4 inch of water.

6. **Economic Benefits** (This objective was not met)
   - **Purpose:** To show how economically feasible the proposed technology is.
   - **Metric:** Energy savings, cost of retrofit/technology, and cost of maintenance measured in dollars while payback period will be measured in years.
   - **Data:** Energy savings will be calculated based on energy demand measurements. The energy demands by the air handler fan and condensing unit are calculated from their measured power uses which are recorded every 5 seconds. The energy savings are calculated by comparing the energy demands with and without the use of the PCM technology utilizing the weather normalization approach.
   - **Analytical Methodology:** The payback period and savings-to-investment ratio will be calculated using the National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis: ECIP Project.
   - **Success Criteria:** Energy savings from the PCM module should yield a less than 6 year pay-back period.
   - **Result for PCM-filled Ceiling Coils:** The current design of the PCM-filled ceiling coils placed under ceiling registers could not meet the 6 year pay-back period. A redesign focusing on higher energy density storage, faster recharging time, and reduced manufacturing cost is necessary to approach this target.
   - **Result for Peak Load Shaving PCM Coil:** The demonstration showed that the current design for the 6 hours PLS coil could not meet the target 6-year payback period. In regions with high fluctuation in peak price and large daily ambient temperature changes such as Sacramento, CA, the current design could achieve a 22 year pay-back period with a product lifespan of 30 years. If night-time air recharging was used, the pay-back period could occur in 14 years. Improvements that will help approach the target

payback period include obtaining PCM with higher specific thermal storage, which will reduce the unit footprint and cost.

7. **Ease of Use and Maintenance** (This objective was successfully met)

- **Purpose**: This qualitative Performance Objective will determine the convenience of DoD wide implementation of the technology.
- **Metric:** This Performance Objective will be measured by the ability of a technician-level individual to service and maintain the technology.
- **Data:** Feedback from the technician on the usability and maintainability of the PCM coild will be gathered from the maintenance log.
- **Success Criteria:** To ensure success, a single field technician should be able to effectively use and maintain the module with minimal training.
- **Result for PCM-filled Ceiling Coils:** The PCM ceiling coils can be installed by field technicians with proper training. After the installation, the PCM ceiling coils operated passively and did not require additional adjustments or maintenances.
- **Result for PCM Coil for Peak Load Shaving:** Field technicians with proper training can install The PCM PLS coil. The PLS coil operated passively and did not require additional adjustments or maintenances. Therefore, no additional work by field technician was needed for the PLS coil. A single field technician with ECU training only requires minimal additional training to check and handle the operation of the PLS coil.

4 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE DESCRIPTION

The demonstration building is the relatively new exercise gym, Building 9732, located on Tyndall AFB, Florida. Figure 10 shows Tyndall AFB and demonstration site locations. This site was selected for several reasons:

1. Tyndall AFB Civil Engineering Squadron (325th CES) and Air Force Civil Engineer Center (AFCEC) Energy Group Manager's significant interest in this project
2. Its limited occupancy and use; and
3. Its recent construction and compliance with latest building codes.

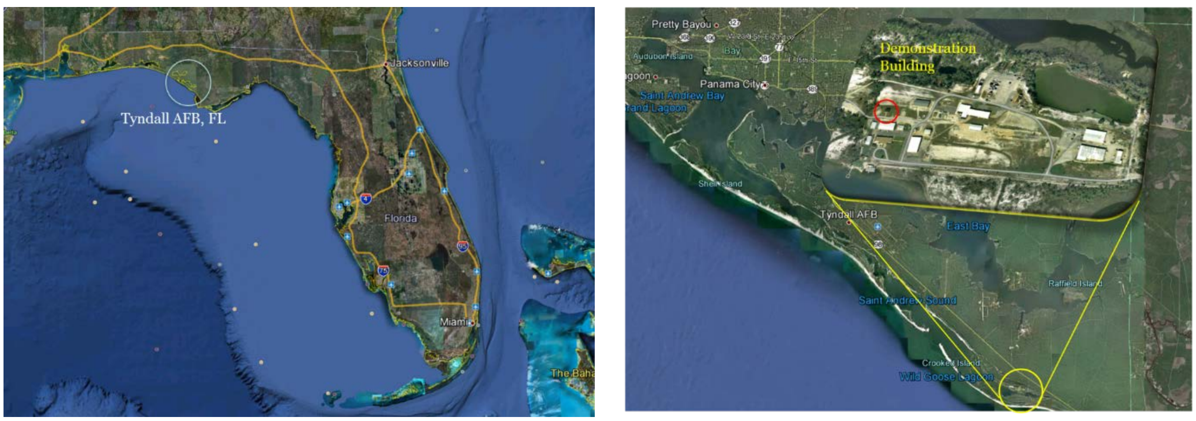


Figure 10: Tyndall AFB and Demonstration Building Locations

Demonstration Site Description

Building 9732 is 1,200 square feet and one story. It has an exercise room; two locker rooms, one for men and the other for women; and a mechanical room, Figure 11. The building's main entrance and all of its windows are on the south wall. There are no surrounding buildings or trees in the immediate vicinity, so the building is directly exposed to daily solar radiation.

Originally, two 3-ton condensing units with a combined 2,100 CFM air handler supplied conditioning to Building 9732. However, this effort's preliminary testing lead to Gulf Power, (local power company) performing a Manual N Load calculation. This calculation showed the building should be equipped with a 4-ton split air conditioning system. This system was installed prior to any data collection. Building 9732 has two 200 CFM exhaust louvers on the west wall and a 400 CFM makeup louver on the north wall.

Figure 11: Demonstration Building, Building 9732 at Tyndall AFB, FL.

Figure 12 shows Building 9732's duct layout. There are 9 registers in the main exercise room (labelled 1-9), one register in the men's restroom (10) and one register in the women's restroom, (11). Air is delivered to these registers by the main 18" x 18" duct that runs through the building's attic space. In the exercise room, the main duct is reduced to 16" x 14" before registers 4-6, and is further reduced to 12" x 12" before registers 1-3. Registers 3, 6, and 9 are connected to the main duct with 10" flexible circular duct, and all other registers are connected with 8" flexible circular duct.

This duct layout produces flow rates shown at each register in Figure 12. These are the flow rates each CC experiences when installed. Registers 3, 6, and 9 have the highest flow rates because are near the south wall which has windows. All other registers in the exercise room have slightly lower flow rates, and restroom registers have the lowest flow rates.

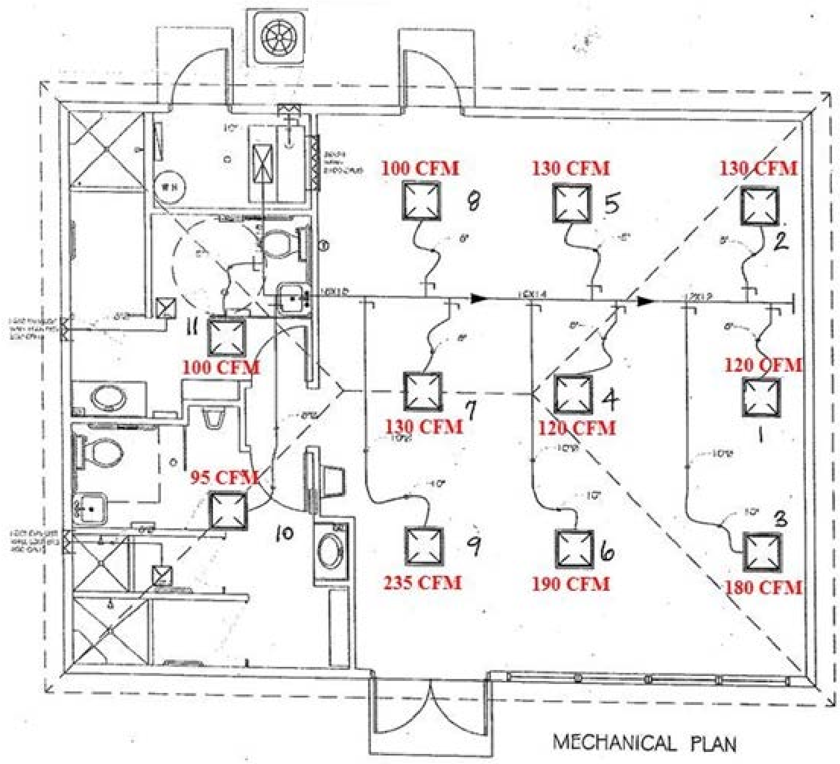


Figure 12: Demonstration building mechanical plan showing duct path, registers, and measured air flow rates at each register (Red Letters).

Key Operations

Tyndall AFB is a training base, while 9700 area hosts AFCEC activities. There was no impact on the demonstration efforts due to the military or AFCEC operations. The demonstration received full support from the 325th CE Squadron and AFCEC Energy groups.

4.2 FACILITY/SITE CONDITIONS

Tyndall AFB is located in a hot and humid climate region; during the hot season (May to October), ambient temperature lows range from mid to high 70s°F. While Tyndall AFB's climate represents an extreme condition for PCM use, this demonstration will provide valuable data for implementing this technology throughout the USA.

Other Concerns

The approved AF-Form 332 allowed us to use the building, reconfigure the air handling equipment and ducts, and keep the building thermostat set at 72ºF.

Tyndall AFB Civil Engineering Squadron has been supporting this demonstration effort, and the base Energy Manager and his group worked with ARA to make this effort a success. No permits were needed, and there were no potential regulations at federal, state or local levels. There were two requirements associated with the demonstration:

1) Civil Engineering Request System: This requirement was for using or making changes to a facility. ARA worked with the facility manager who submits AF-Form 332 to Base Civil Engineering Request System for placing equipment and altering the building. After AF-Form 332 was approved, all modifications, equipment install, and work being performed is communicated to the facility manager prior to any action. The facility manager handles internal procedures or directs us to the proper contacts.

2) Information Assurance: This requirement was to obtain approval to place a nongovernment data-acquisition computer with remote access using a mobile broadband service. This service is required to monitor demonstration building data before and after installing proposed technology. Working with the Computer Support Help Desk through AFCEC Energy Group Manager, Computer Support personnel handled internal procedures and resolved all computer issues to make this setup work at Tyndall AFB. Conditions set for operation were:

    a. The computer with the broadband wireless card is to be used for data collection, transmission and manipulation.
    b. The computer will not be used as an internet terminal for surfing or checking e-mail.
    c. All equipment (Computer, Monitor, Keyboard, sensors and others) will be marked as ARA property, and will also state that it is only to be used for data collection, manipulation, and transmission under the contract number.
    d. Get approval from facility manager about the installation of the external broadband antenna even if it is only a magnetic mount.

5 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

Testing was designed to determine the two PCM technologies' impact on the energy use for Tyndall AFB Building 9732. Each technology's performance was evaluated against the building baseline performance using the performance objectives outlined in Table 3. As weather conditions can vary significantly from year to year, a weather normalization approach was used to accurately compare the performance of the PCM technologies to the baseline.

Data on room temperature and humidity distribution, ECU power, total building power consumption, and weather data were collected during the test periods. All tests were conducted using a room thermostat temperature setting of 72^{o}F and the same air conditioning equipment.

Since two PCM technologies were to be evaluated concurrently, it was important to design the test schedule to allow enough collected data on each technology to make an accurate comparison with the baseline. The PLS coil was only tested every other week until enough data were collected to demonstrate that peak hour air conditioning could be shifted to off hours while maintaining comfortable room conditions. All remaining time was devoted to collecting data on the PCM-filled coils under ceiling registers.

During demonstration, ECU operation was dictated by a LabView program. This program allowed the thermostat to control the air conditioning system as in the baseline, or engaged the condenser unit and evaporator fan according to the PCM technologies' needs. The LabView program also controlled automatic airflow dampers.

5.2 BASELINE CHARACTERIZATION

5.2.1 Sampling Protocol

Baseline tests established reference conditions for building temperatures, humidity, and equipment's electricity usage. Sensors were installed at the demonstration building to establish baseline performance weather dependence and examine building behavior. Table 4 and Figure 13 show sensor quantities and locations.

Table 4: Baseline Sensor Type, Quantity, and Location

Location	Type K Thermocouple	Relative Humidity	Power Transducer	Door Sensor	Pressure
Main Room	29	5	0	2	
Men's Bathroom	2	1	0		
Women's Bathroom	2	1	0		
Attic Space	5	0	0		
Mechanical Room	1	1	3		2
Air Handler (Mech. Room)	3	1	0		

Red, blue, green, yellow, purple, brown circles in Figure 13 indicate thermocouple, relative humidity and power transducer, pressure transducer, flow meter and door sensor locations

respectively. 29 thermocouples were installed in the main exercise room, 2 in the men's restroom, 2 in the women's restroom, 1 in the mechanical room, 3 in the air handler inside the mechanical room, and 5 in the attic space above the main exercise room. Attic space thermocouples were positioned above the exercise room's center and four corners. There were 5 relative humidity sensors in the main exercise room, 1 in each restroom, 1 in the mechanical room, and 1 in the air handler. 3 power transducers measured air handler, condenser unit, and total gym power. Pressure transducer measured air handler pressure drop to get total system pressure drop for redundant flow rate calculations and ensuring that technology does not introduce adversely high pressure drops. Door sensors were used to track occupancy. The volumetric airflow rate was measured using a Nelson & Company duct mount station, which was installed in the duct directly above the air handler in the mechanical room ceiling.

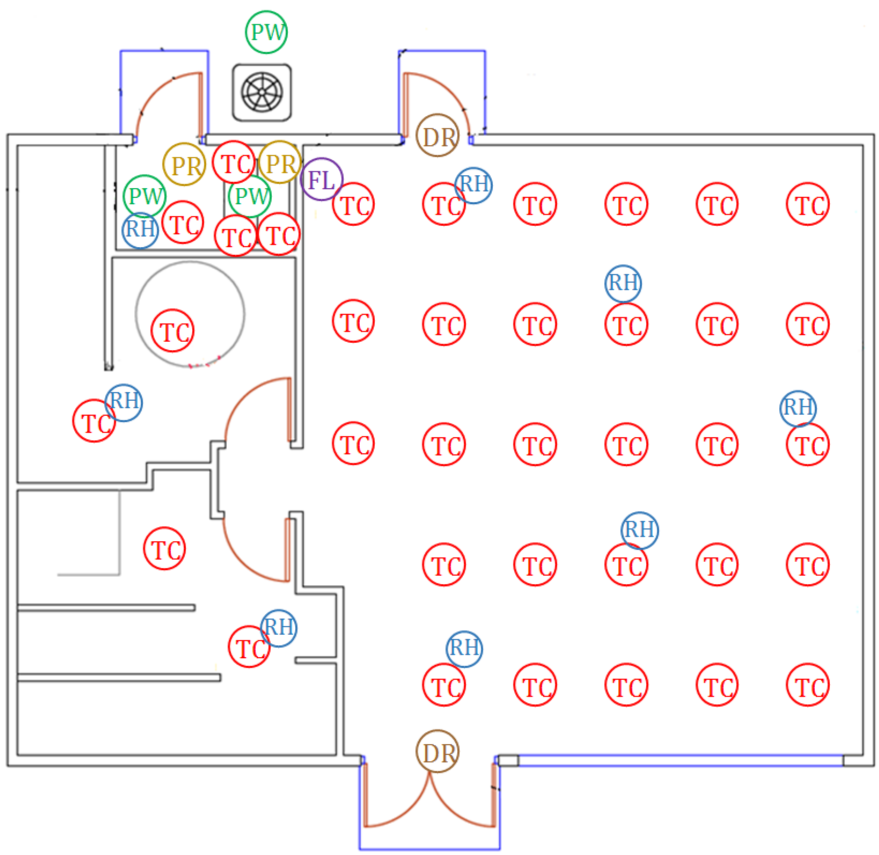


Figure 13: Demonstration Building Sensor Locations. Sensors Key – TC: Thermocouple; RH: Relative Humidity; DR: Door Open/Close; PW: Power; PR: Pressure; and FL: Flow

Weather data were also collected at a location in close proximity to the building using a NovaLynx weather station. The weather station measured solar radiation, ambient temperature, and ambient relative humidity, Table 5.

The sensors and weather station were connected to a National Instruments (Compact RIO) cRIO 9014 industrial controller along with a cRIO 9116 eight-slot chassis. The chassis had three NI 9213 thermocouple input modules, four NI 9203 current analogue input modules for power, humidity and weather station connections, and one NI 9201 voltage input module for door sensors.

Ethernet connected the cRIO controller to a Dell OptiPlex 960 desktop computer that runs National Instrument's LabView Developer Suite 2011 software with Real Time option. During demonstration, data collected at a sampling frequency of 1Hz and digitally written to LVM files by LabView. Retrieving files and monitoring the system remotely was accomplished using a Raven XE modem, Verizon Mobile Broadband service, and Window's Remote Desktop.

Table 5: Weather Data Recorded By Novalynx Station

Measurement Type	**Quantity**
Temperature	1
Relative Humidity	1
Wind Speed	1
Wind Direction	1
Barometric Pressure	1
Rain Gauge	1
Solar Radiation	1

5.2.2 Key Baseline Results

In addition to requiring baseline data for determining energy savings (Section 6), this data was also required for designing the technology. In particular, the building heat loads and radiation patterns were needed for sizing and placing heat exchangers.

Daily building heat loads may be determined by summing heat removed by the ECU system, Q. This in turn may be determined from the evaporator coil's temperature drop and the air mass flow rate as:

$$Q = \dot{m}C_p(T_{in} - T_{out}) \qquad \text{Equation 1}$$

Temperatures before and after the evaporator coil (T_{in}, T_{out}) were measured using thermocouples inside the air handler. $\dot{m}$ was determined using the total volumetric flow rate from Figure 12 and assuming constant air density. Air specific heat, C_p, was taken to be constant.

Figure 14 shows Q (blue) and ambient temperature (yellow) for a typical day. Heat infiltration rate (red) was estimated by hourly averaging Q and inverting its sign. The area under this curve represents energy added to the building during that time in kJ. For the day examined, the largest amount of energy added to the building while the condenser unit was off was 3,233 kJ.

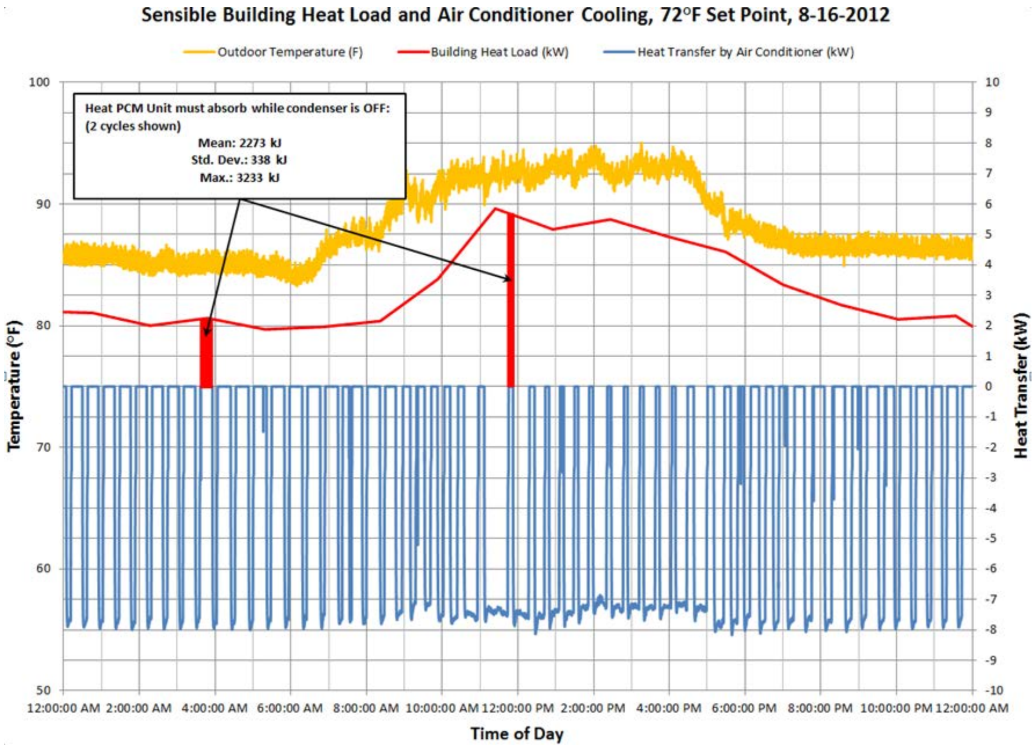


Figure 14: Heat transfer in and out of the building on a hot day, 8-16-2012

Figure 15 shows the demonstration building roof configuration and orientation, while Figure 16 shows solar radiation on the demonstration building surfaces based on data collected on May 13, 2012.

Figure 15: Demonstration Building Roof Configuration and Orientation

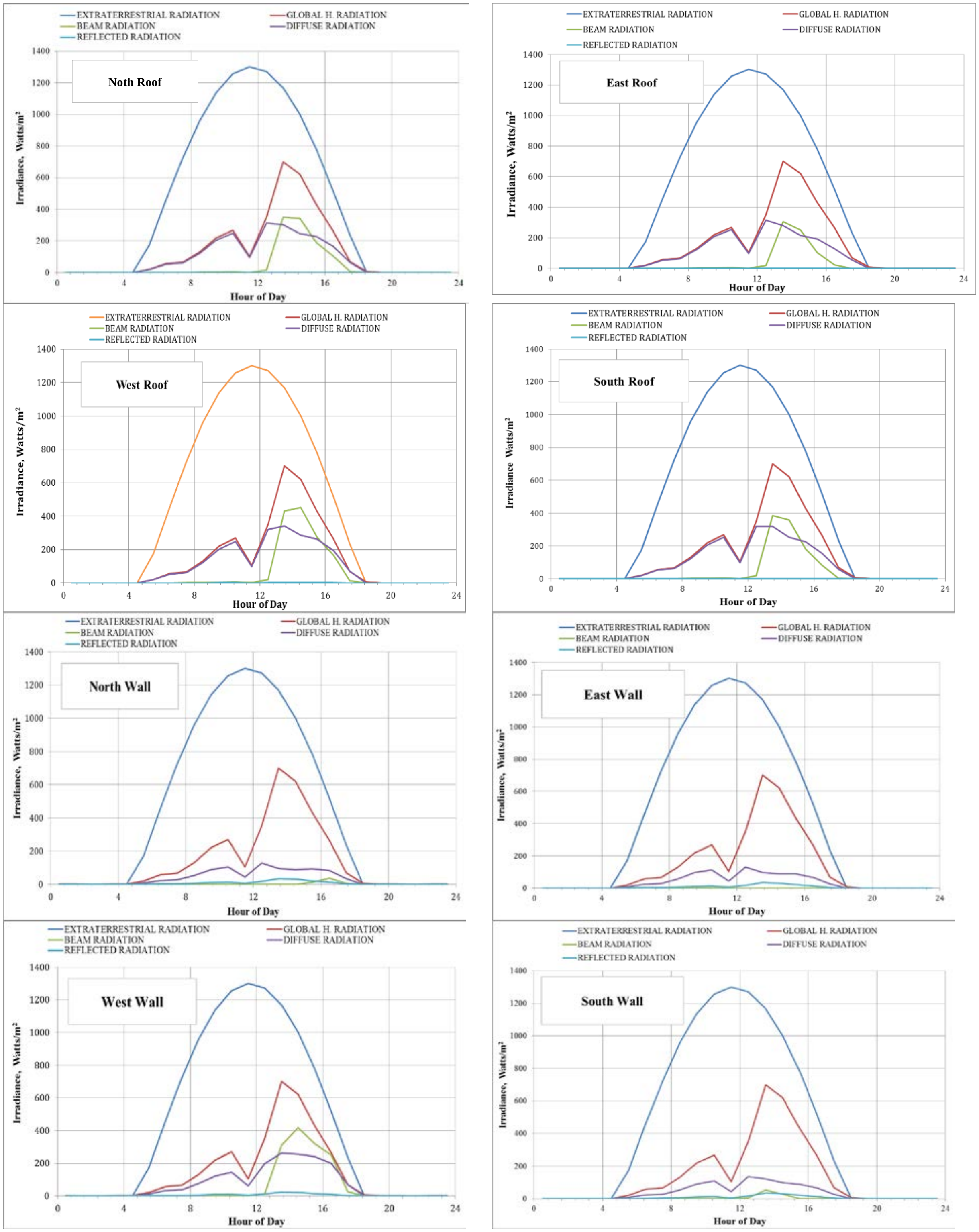


Figure 16: Direct, Diffuse, and Reflective Solar Radiation on Each Surface of the Demonstration Building for May 13, 2012 Baseline Data

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 Ceiling Coils Installation

Eleven PCM-filled coils were installed under ceiling air registers located as illustrated in Figure 17. Ceiling coils were suspended inside each room directly beneath registers in the drop ceiling. This way ceiling coils could cool the room through natural convection when the air handler's evaporator fan was off.

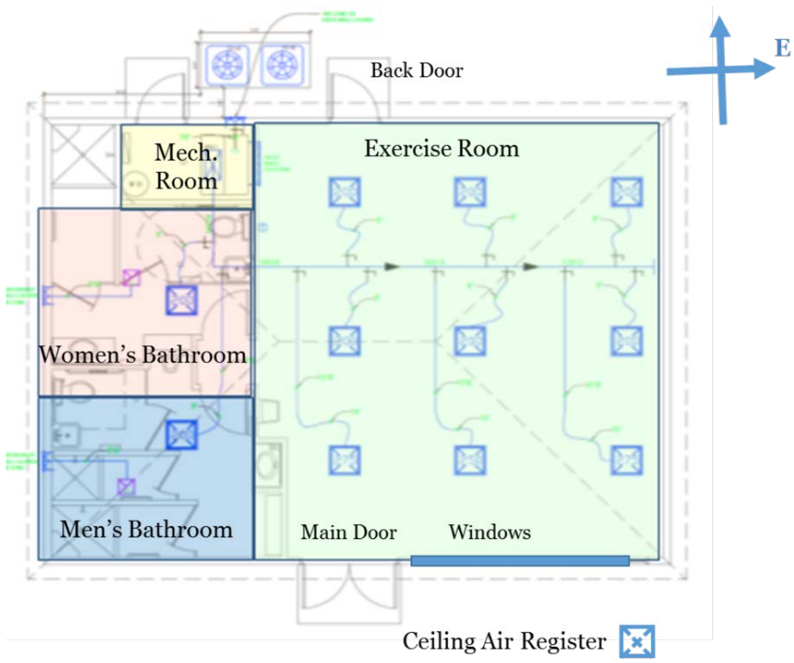
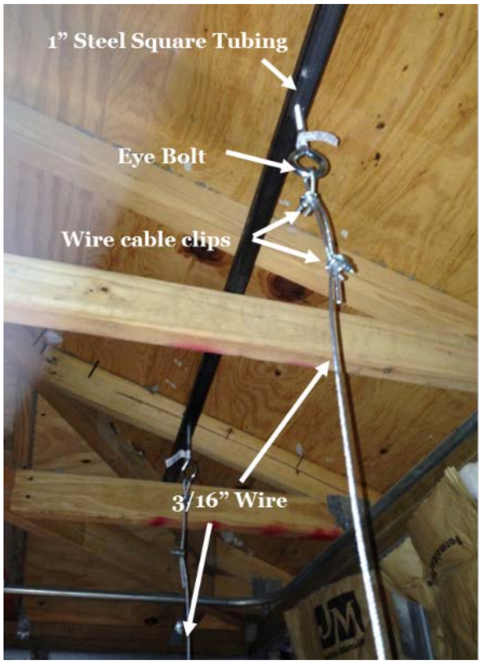


Figure 17: Building 9732 ceiling register locations

To ensure peak ceiling coil performance, all air emitted by ceiling registers needed to pass through the coils. Therefore, ceiling coils had to be mounted flush with the existing drop ceiling and sealed with a gasket. However, at approximately 40 pounds per coil, the drop ceiling would not be able to support coils' weights. Therefore, coils were suspended from ceiling joists in the attic. Figures 18 through Figure 20 document the ceiling coils' installation procedure.



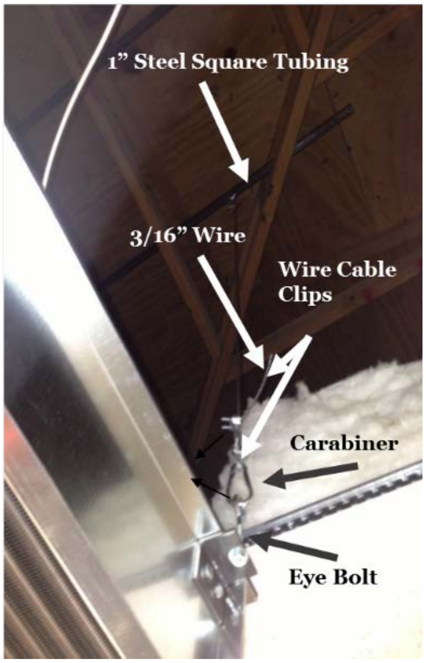


Figure 18: (Left) Attic space with 1" steel square tubing on top of ceiling joists to support PCM-filled ceiling coils (Right) View looking up into the attic showing a ceiling coil attached to cables suspended from square tubing

Figure 19: Drop ceiling during installation process with three ceiling coils located under registers and two registers before coil placement

Figure 20: Exercise room complete ceiling coil installation

Two 1" steel square tubing (1/8" wall) sections were placed over attic ceiling joists and used to suspend each ceiling coil, Figure 18, Left. This allowed ceiling coils to be flush with registers in the drop ceiling. Two holes were drilled through each piece of square tubing, and eyebolts were threaded through with nuts placed on the back. Wire was then threaded through the eyebolts and secured using wire clamps, Figure 18, Right. The lower end of the wire was used to attach the ceiling coil, Figure 19. Wire was fed through a carabiner and then attached to another eyebolt mounted on the ceiling coil's flange. With this attachment method, ceiling coils could be easily uninstalled by unclipping carabiners from eyebolts mounted to coil flanges.

To prevent ceiling coils from shifting, wires were kept as close to vertical as possible by positioning square tubing directly above two corners of each coil. Since each square tubing piece could only be lined up over two corners, two pieces of square tubing were needed to support each coil.

5.3.2 Peak Load Shaving Installation

To simplify installation, the PLS coil was placed on the exercise room's floor along the north wall, Figure 21. It was positioned carefully to avoid blocking exits in accordance with the building's fire codes. New duct branches were then constructed to integrate the PLS coil into the existing ECU system and allow closed loop regeneration, Figure 22. The integration duct branch started above the mechanical room where the existing duct made its first 90 degree bend. From there, the duct went down into the exercise room through the drop ceiling and fed through the large coil before going back up through the drop ceiling and reattaching to the existing duct, Figure 23. Four automatic airflow dampers (AAD1 to AAD4) were located in the new duct branches to control PLS coil use as directed by a LabView program.

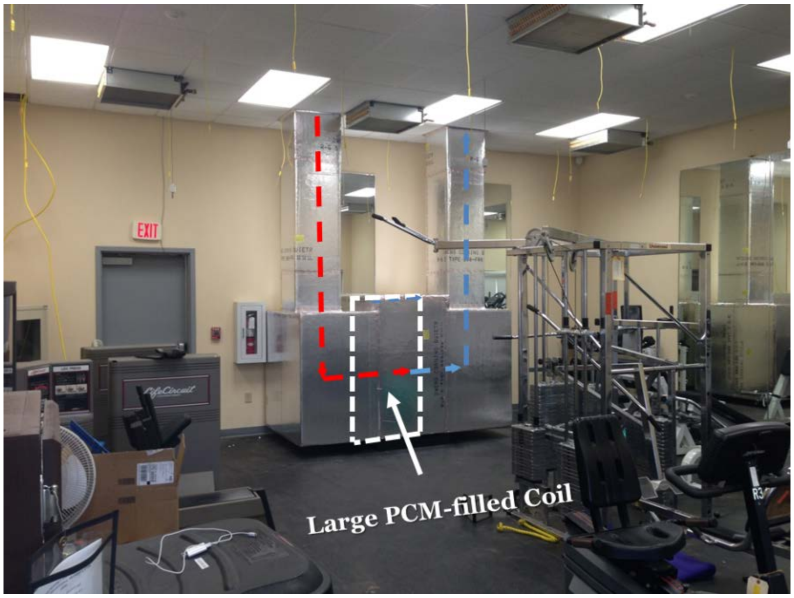


Figure 21: PLS coil location on exercise room's north wall. Direction of airflow through the coil is indicated by the red arrows (air into coil) and blue arrows (air out of coil).

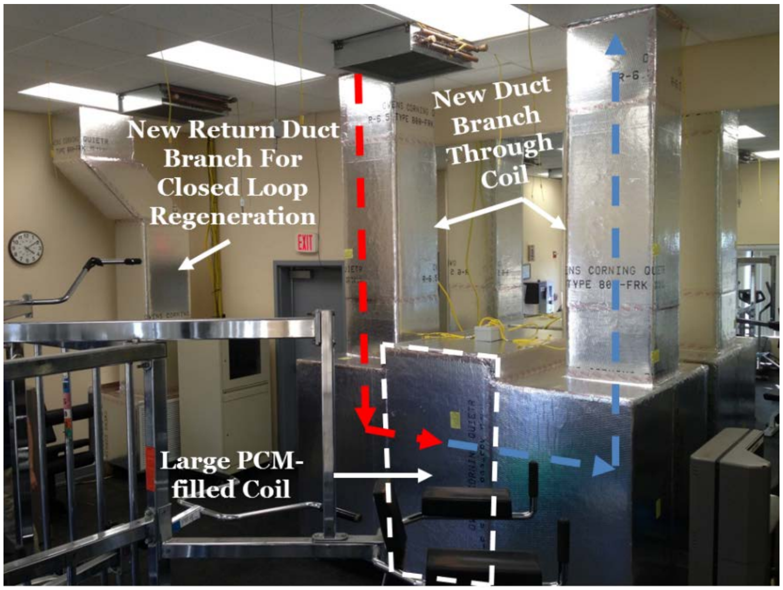
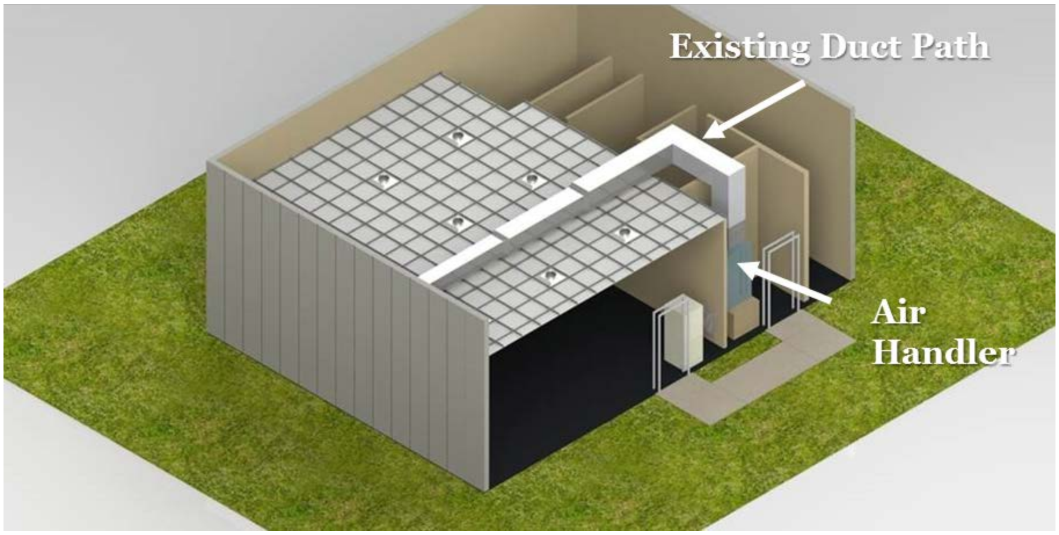


Figure 22**:** New PLS duct branches. Direction of airflow through the coil is indicated by the red arrows (air into coil) and blue arrows (air out of coil).

Tyndall AFB 9732 Building Baseline

Existing HVAC Duct Layout



Tyndall AFB 9732 Building Large Coil Install

New Duct Branch and Dampers Locations Layout

Figure 23: SolidWorks 3D Render of the Demonstration Building Showing Existing Duct Path (Top) and New Duct System After Integrating the Large PCM-Filled Coil (Bottom)

5.4 SAMPLING PROTOCOL

5.4.1 Additional Sampling for Tech Demonstration

Building and weather related sensors used during demonstration were the same as those described in Section 5.2.1. Additional sensors were located inside PCM modules to gain insight on the

behavior of the PCM. These additional sensor readings were recorded by LabView in a separate LVM file at a sampling frequency of 1Hz.

Three ceiling coils in the exercise room were instrumented, Figure 24. In these ceiling coils, inlet and exit air temperatures and PCM temperatures inside the first and last tube rows were measured using thermocouples, Figure 25.

Thermocouples in the PLS coil measured air temperatures at the coil's inlet and exit, and PCM temperatures at three locations in the first and last row tube rows, Figure 26. PCM probes were inserted into copper tubes to a depth that measured PCM temperature at the airflow's center. Table 6 summarizes the additional sensors that were installed for the demonstration.

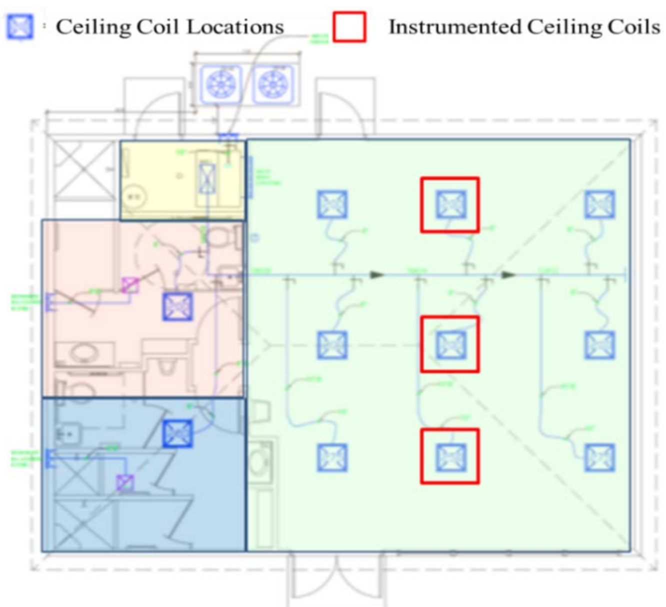


Figure 24: Instrumented Ceiling Coil Locations In The Demonstration Building

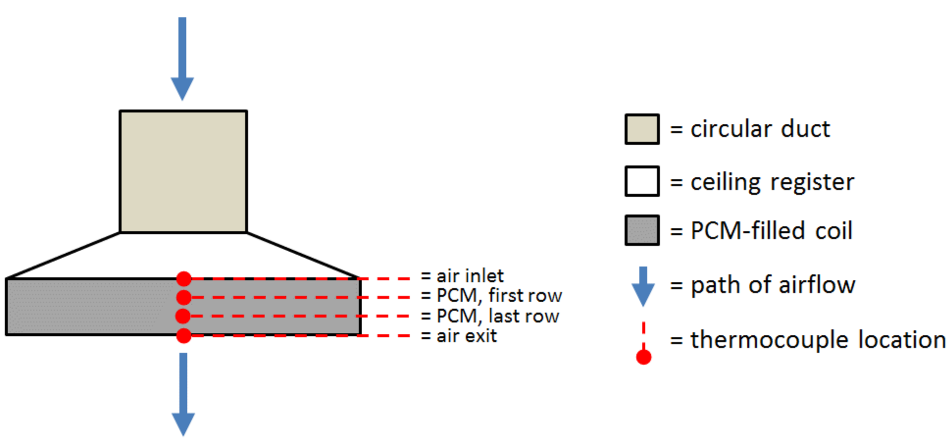


Figure 25: PCM-filled Ceiling Coil Thermocouple Locations

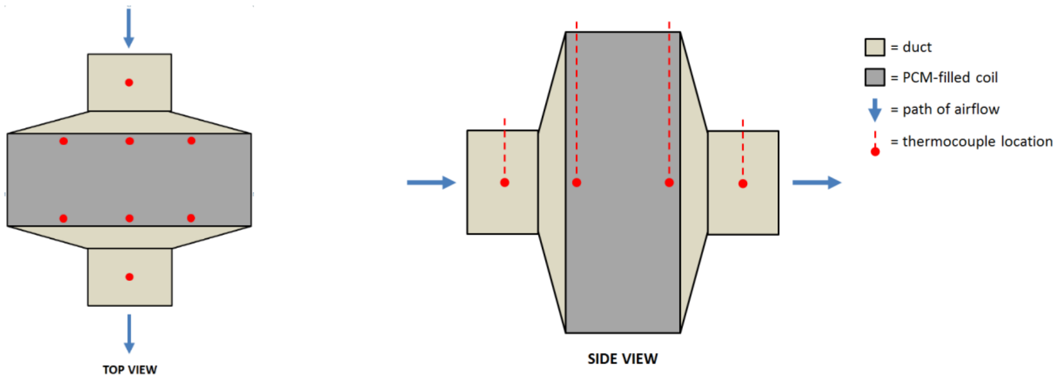


Figure 26: Peak Load Shaving Coil Thermocouple Locations

Table 6: Sensors Added For the Demonstration

Location	Type K Thermocouple	Air flow
Peak Load Shaving Coil	8	0
Ceiling Coils	12	0
Duct	0	1

5.4.2 Quality Assurance

Quality assurance during sampling was provided in several ways. For physical measurements, the dense sensor layout ensured that if a sensor failed, there was another measurement in close proximity. For data, LabView recorded two files each day for redundancy. To improve the quality of collected data and eliminate noise, ARA used LabView's moving average function to smoothed them.

5.5 OPERATIONAL TESTING

5.5.1 LabView Controls

Testing the PCM technologies required control over the ECU's condenser unit and air handler fan and automatic airflow dampers. Control was achieved using a LabView program that operated relays connected to these components. This program specified when each technology was used and their operational schemes. Operational schemes are discussed in more detail in the following two subsections.

Figure 27 shows a screenshot of the LabView Virtual Instrument user interface for the program that monitored and controlled the two PCM technologies in the demonstration. Ceiling coil and PLS coil temperatures were shown on left and right respectively. ECU operation and damper positions were shown in the center; green lights indicate when LabView is engaging components. Gauges on the bottom show air handler and condenser unit power usage, airflow measured by a duct mount station, and current room temperature measured next to the thermostat. The VI

includes several user specified parameters to make small adjustments to the PCM technology's operation.

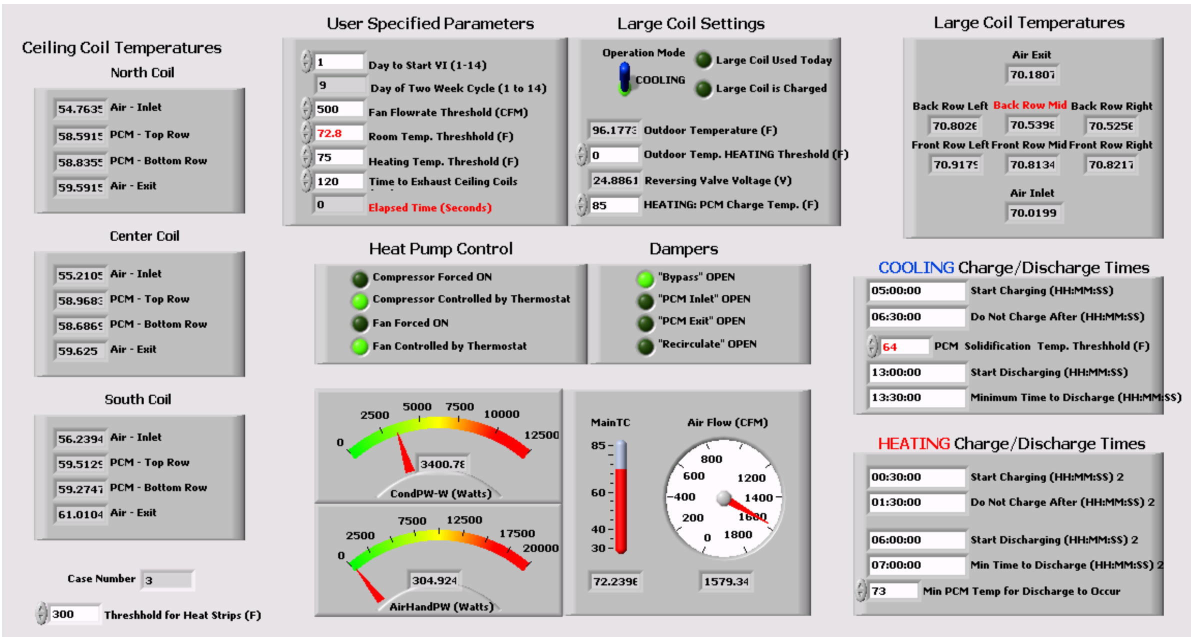


Figure 27: Screenshot of LabView Virtual Instrument (VI) Used to Control the Operations of the Two PCM Technologies During the Demonstration

5.5.2 Ceiling Coil Testing

Normally, the fan and condenser unit run simultaneously to cool the room. When the room temperature reaches the thermostat set point, the condenser unit is turned off and the air handler fan runs for an additional 90 seconds to take advantage of the still-cold evaporator coil.

Normal air conditioning operation was slightly modified to optimize ceiling coils use. Originally, the plan was to run the air handler fan continuously, so PCM could benefit from forced convection during both freezing and melting. Forced convection greatly enhances heat transfer to and from PCM, and expedites phase change. However, pre-demonstration testing showed continuous fan usage consumed significant energy over daily. Therefore, the air conditioning system operated as normal, but the fan was forced to run for 2 minutes each cycle prior to the condenser unit engaging. This operation allows PCM to benefit from forced convection while absorbing heat from the room, but uses significantly less energy than if the fan ran continuously. Additionally, ceiling coils can still cool the room by natural convection while the fan is off.

To implement this operation, communication between the thermostat and condenser unit was routed through the LabView controller. This controller then adjusted normal air conditioning operation resulting in the following pattern each cycle:

1. Room temperature exceeds thermostat cooling set temperature. Thermostat turns on fan (Relay 1, Figure 28, closed). and attempts to turn on condenser unit. Condenser unit power is blocked by LabView controlled relay (Relay 2, Figure 28, open).
2. Measured fan is on when measured power exceeds 150W. LabView takes fan to be on and starts a two-minute timer.
3. Two-minutes elapse and LabView controller closes relay (Relay 2, Figure 28) allowing thermostat to power condenser unit.
4. LabView waits for condenser unit to turn off at the end of a cooling cycle, and then opens the relay (Relay 2, Figure 28). The thermostat cannot turn it on next cycle. LabView determines condenser unit is off when measured condenser unit power < 500W

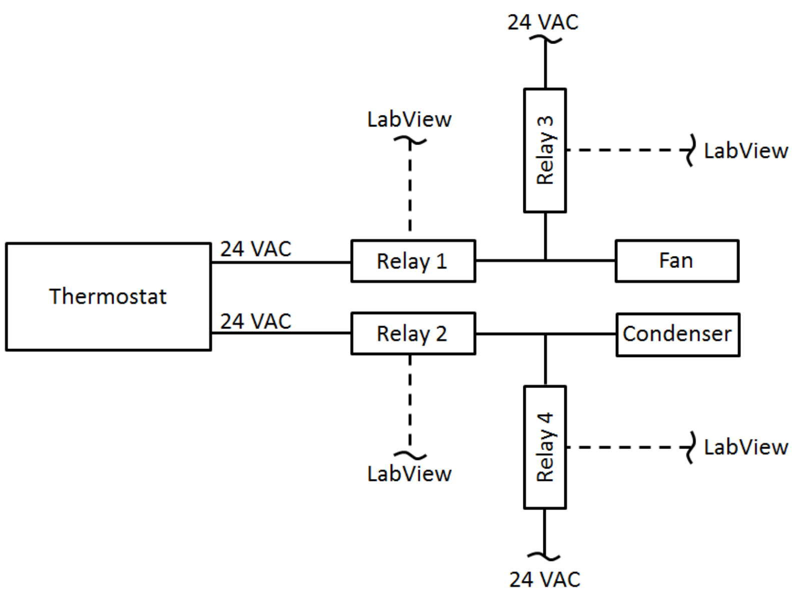


Figure 28: Schematic of LabView/thermostat connections

While ceiling coils installation was completed on Sept 9, 2013, testing using the above 4-step sequence began on Nov 1, 2013 following PLS coil installation. From this point forward during the demonstration, 'normal air conditioning operation' refers to the 4-step sequence listed above. Ceiling coil testing took place every day the PLS coil was not used. Testing was completed on November 30, 2014.

5.5.3 Peak Load Shaving Testing

Closed Loop Freezing

To ensure PCM was fully frozen throughout the PLS coil, a dedicated freezing period in the morning was added where the ECU supplied cold air to the PCM coil in a closed loop. The control scheme for this test consisted of three operation modes as follows:

1. *Normal Operation* from 12:00 AM until 5:00 AM

2. *Closed Loop Regeneration* from 5:00 AM until the PCM is fully frozen. Fan and condenser unit are forced on (Relays 3 and 4 closed, relays 1 and 2 open Figure 28) LabView's criteria for complete freezing was measured PCM temperature in last tube row $\leq$ 63.5°F (determined experimentally).
3. *Normal Operation* from the end of step 2) until 1:00 PM
4. *PLS* coil continuously absorbs room heat until it is depleted or unable to keep the room cool. LabView forces air handler fan on (Relay 3 closed, Relays 1 and 4 open Figure 28). This phase ends when the room thermostat calls for cooling (Relay 2 closed, condenser unit power monitored). This means that even if there was unused PCM capacity, the PLS coil was not absorbing room heat load quickly enough to maintain the room at set temperature. At this point, even if the large PCM coil had unused capacity, use of the PLS coil was discontinued until the next test day.
5. *Normal Operation* for the remainder of the day:

Switching between these modes of operation were accomplished through damper changes and dictated use of air conditioning components governed by the LabView program. Figure 29 shows damper configurations and airflow paths for the three modes.

Closed loop freezing has several benefits that increase the heat transfer rate from the PCM module to the air and reduce solidification time. These factors are discussed as they pertain to the heat transfer rate, Equation 2:

$$\dot{q} = \dot{m} * C_p * (T_{INLET} - T_{EXIT}) \qquad \text{Equation 2}$$

Where:

$\dot{q}$ = heat transfer rate (kW) at which heat is transferred to the air as it passes through the PCM module. If the heat transfer rate is increased, the solidification time will decrease.

C_p = specific heat of air (kJ/kg°K),

$\dot{m}$ = mass flow rate of air (kg/s),

$(T_{INLET} - T_{EXIT})$ = The temperature difference (°K) between the air at the inlet and exit of the PCM module. The closed loop configuration increases $(T_{INLET} - T_{EXIT})$, increasing $\dot{q}$ and decreasing solidification time.

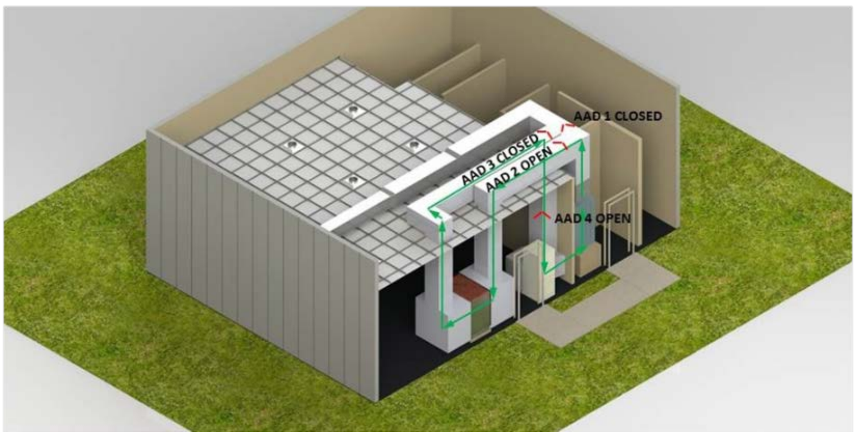
The PLS coil was installed on November 1, 2013. Since it was designed for cooling with peak load shaving, limited testing was done in winter. Most PLS coil testing was from March 2014 to July 2014.

Tyndall AFB 9732 Building Large Coil Install

Normal Operation

Tyndall AFB 9732 Building Large Coil Install

Closed Loop PCM Regeneration



Tyndall AFB 9732 Building Large Coil Install

PCM Room Control

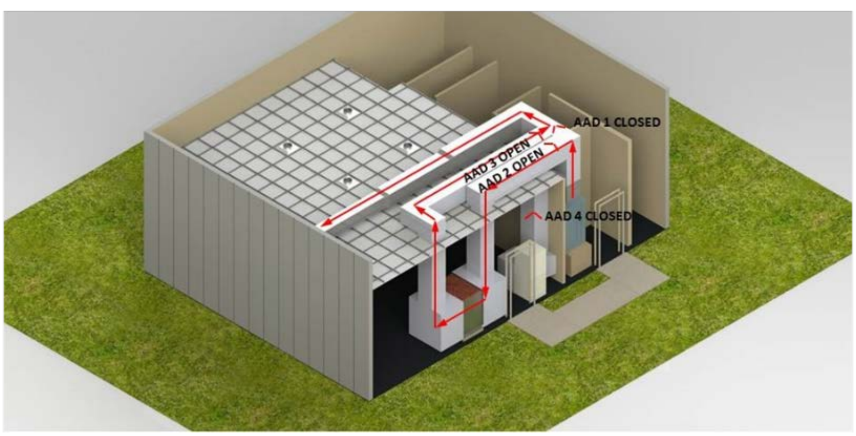


Figure 29: Diagram Showing the Three Modes of Operation Using the Large PCM-Filled Coil for Peak load Shaving. Normal Operation (Top), Closed Loop PCM Regeneration (Middle) and PCM Room Control (Bottom)

Open Loop Regeneration

Open loop regeneration was tested in an attempt to reduce system complexity. In this mode of operation, the air path was constant (Figure 29, bottom). LabView's control scheme for this test was:

1. Normal air conditioning operation from 12:00 AM until 1:00 PM. Air is routed through PLS coil
2. Condenser unit is prevented from engaging (Relay 2 and 4, Figure 28, open), fan is forced on (Relay 3, Figure 28, closed). PLS coil absorbs heat from the room until it is depleted or unable to keep the room cool (Relay 2, Figure 28, closed and condenser unit power monitored)
3. Normal air conditioning operation for the remainder of the day

In this 3-step control scheme, PCM regenerated throughout the day. When the ECU cools the room, cold air flows through the PLS coil and it partially freezes. Once the room cooled, the fan runs for 2 minutes after the condenser unit is off. Thus, PCM experiences significantly more forced convection during freezing than melting. At 1:00 PM, the fan is turned on and PCM absorbs room heat while it melts. The condenser unit stays off until the PCM capacity is depleted, or until the thermostat calls for air conditioning. Normal air conditioning operation is then resumed and PCM begins to gradually freeze again until it is used again at 1:00 PM the following day. The only control necessary for this control is forcing the fan to run while the PLS coil is used to condition the room during peak hours.

6 PERFORMANCE ASSESSMENT/RESULTS

6.1 WEATHER NORMALIZATION

To facilitate accurate performance comparisons between retrofitted and original ECU systems and calculate resulting actual savings, we developed a new statistical weather normalization method. The new method includes solar radiation and relative humidity as independent variables. Including solar radiation accounts for sunny and cloudy day impacts on building heat loads.

Performing multiple regression analysis using baseline data for ECU energy consumption as a dependent variable and ambient temperature, ambient humidity ratio, and global horizontal solar radiation as independent variables, demonstration building energy consumption can be derived as:

$$E_{BL} = A + B\ CDD \times\ T_{sol}^{\alpha}\ \times\ H_r^{\beta} \qquad \text{Equation 3}$$

Where E_{BL} is the baseline energy consumption, A, B, α and β are regression coefficients, T_{sol} is the sol-air temperature, and H_r is ambient air humidity ratio. Equation 3 is referred to as the non-linear model. A linear model was also considered:

$$E_{Hd} = a + b \times CDD_d +\ c \times T_{sol} + d \times H_r \qquad \text{Equation 4}$$

Where:

E_{Hd} = Predicted baseline ECU energy per day

a, b, c, d = Linear regression coefficients

However, the linear model has significant collinearity between the model parameters [7], specifically, the collinearity between the ambient temperature, solar insolation and humidity. This results in unstable and unreliable regression results (we have confirmed this instability using the baseline model data). As a result, the linear model is limited to the cooling-degree days per day only and is therefore reduced to:

$$E_{Hd} = a + b \times CDD_d \qquad \text{Equation 5}$$

One way to overcome this difficulty is through the use of principal component analysis (PCA) [8]. In this project, we use the nonlinear model to eliminate collinearity between the independent variables in Equation 3 and provide stable and reliable regression results.

The coefficients A and B are linear and can be found using normal linear regression routines given an estimate of the two nonlinear parameters, α and β. A nonlinear search to determine new values for α and β, which maximizes the regression R^2 value is then performed and the linear coefficients are re-evaluated until the value of R^2 is converged to a specified accuracy. The Nelder–Mead method or downhill simplex method [9] was used to search for α and β.

6.1.1 Sol-air Temperature

T_{sol} represents the equivalent ambient temperature that gives the same heat flow rate into a surface as would the combination of incident solar radiation and convective and radiative heat transfer with the environment [10]:

$$T_{sol} = T_{amb} + \frac{\alpha}{h_o}\,\dot{q} - \frac{\varepsilon\sigma}{h_o}\,(T_{amb}^4 - T_{sur}^4) \qquad \text{Equation 6}$$

The first term in Equation 6 represents convection and radiation heat transfer to the surface when the average surrounding surface and sky temperature is equal to the ambient air temperature, $T_{sur} = T_{amb}$. The last term is the correction for the radiation heat transfer when $T_{sur} \neq T_{amb}$. The second term is the amount of solar incident absorbed by the surface. In Equation 6:

T_{amb} = ambient temperature, in °C (in the last term $T = T + 273$, K)
T_{sur} = surface temperature in ^oK
$\dot{q}$ = total solar incident on the wall in watts/m^2
α = surface absorptivity
ε = surface emissivity
σ = Stefan–Boltzmann constant = 5.670373×10^{-8} W/m^2.K^4
h_o = Convection and radiative heat transfer coefficient W/m^2.C;
$h_o = h_c + h_r$ where h_c is the convection heat transfer coefficient; and h_r is the radiation heat transfer coefficient. Both are given by the following definitions if the wall temperature is known:

$$h_r \cong 4\sigma\,\varepsilon\,T_m^3 \qquad \text{OR} \qquad h_r = \sigma\,\varepsilon\,(T_{amb}^2 + T_{sur}^2)(T_{amb} + T_{sur}) \qquad \text{Equation 7}$$

In most cases the surrounding temperature is the sky temperature, T_{sky}, and is calculated as follows:

The air moisture affects the effective sky emissivity and thus less radiative cooling potential for humid locations. The clear sky emissivity can be estimated by a correlation developed by Berdahl and Martin [11]:

$$\varepsilon_{Clear} = 0.711 + 0.56(T_{dp}/100) + 0.73\,(T_{dp}/100)^2 \qquad \text{Equation 8}$$

Where, ε_{Clear} is the clear sky emissivity, T_{dp} is the dew point temperature, in ^{o}C and can be calculated as [12]:

$$T_{dp} = 243.12*H/\,(17.62-H) \qquad \text{Equation 9}$$

Where H is a function of relative humidity (RH) and ambient temperature T_{amb} in ^{o}C. It is defined as:

$$H = [\log_{10}(RH)-2]/0.4343 + [(17.62*T_{amb})/(243.12+T_{amb})] \qquad \text{Equation 10}$$

Where T_{amb} is the ambient air temperature in °C.

The effective clear sky temperature is then:

$$T_{clear\_sky} = T_{amb}\,(\varepsilon_{Clear}^{0.25})\ °C \qquad \text{Equation 11}$$

T_{sky} is derived from T_{clear_sky} by integrating the effects of cloud cover and atmospheric moisture content. According to Clark *et al* [13, 14, 15]:

$$T_{sky} = (Ca)^{0.25} * T_{clear\_sky}\ °C \qquad \text{Equation 12}$$

Where:

$$Ca = 1.00 + 0.0224*CC + 0.0035*CC^2 + 0.00028*CC^3 \qquad \text{Equation 13}$$

and CC is cloudiness and its value ranges between 0 and 1. It is 0 for clear sky and 1 for totally cloudy sky.

If T_{sur} is not known, a conservative value of h_o of 17 W/m^2.^{o}C can be used. To calculate $\dot{q}$ in the second term of Equation 6, which is the total solar radiation averaged over total area of all walls and roof sections, we used ARA's computer model "SOLARDO" to calculate direct, diffuse, and reflective solar radiation on vertical and inclined surfaces. $\dot{q}$ is given as:

$$\dot{q} = \frac{1}{A_t} \sum_{i=1}^{i=n} A_i\ q_i \qquad \text{Equation 14}$$

Where q_i is the total (Direct + Diffuse + Reflective) radiation for wall "i" with area A_i and A_t is the building total outer surface area.

6.1.2 Cooling Degree Days

CDD is found for each day of baseline data as:

$$CDD_d = \frac{1}{N}\sum_{i=1}^{N}\left\{\left(\frac{(T_{hi}-T_{lo})}{2}\right)_i - T_{BP}\right\}\ ; \quad \frac{(T_{hi}-T_{lo})}{2} - T_{BP} > 0 \qquad \text{Equation 15}$$

Where:

CDD_d = Cooling Degree Days per day
T_{hi} = Daily high temperature
T_{lo} = Daily low temperature
T_{BP} = Cooling Balance Point temperature
N = Number of averaging days

Traditionally, T_{BP} is defined as 65 °F [16], however, each building has its own T_{BP}. Using a structure T_{BP} gives accurate results when comparing energy use before and after a retrofit. The cooling T_{BP} temperature can be thought of as the outdoor temperature at which internal heat generation and heat losses offset solar gains. Outdoor temperatures above this threshold indicate the need for heat removal (cooling).

Using the energy consumption data collected for the ECU system for both the baseline and demonstration systems, T_{BP} can be defined as the temperature at which the energy consumption for the ECU system is zero or negligible.

A new method was developed to determine T_{BP} directly from ECU energy. Linear regressions were performed on ambient temperature vs. ECU energy consumption for both data sets. The intercept values from the regressions provided T_{BP}. Figure 30 shows the data and fit for the baseline data. The linear fit is given by:

$$T_{amb} = 68.897 + 5489E \qquad \text{Equation 16}$$

Where T_{amb} is the ambient temperature in °F and E is the energy used by the baseline ECU unit in kWh. The R^2 value for the linear fit is 0.8.

Similarly, for the demo case, Figure 31, the linear fit is given by with an R^2 of 0.88:

$$T_{amb} = 64.051 + 0.6944E \qquad \text{Equation 17}$$

Therefore T_{BP} is 69°F and 64°F for the baseline and demonstration respectively.

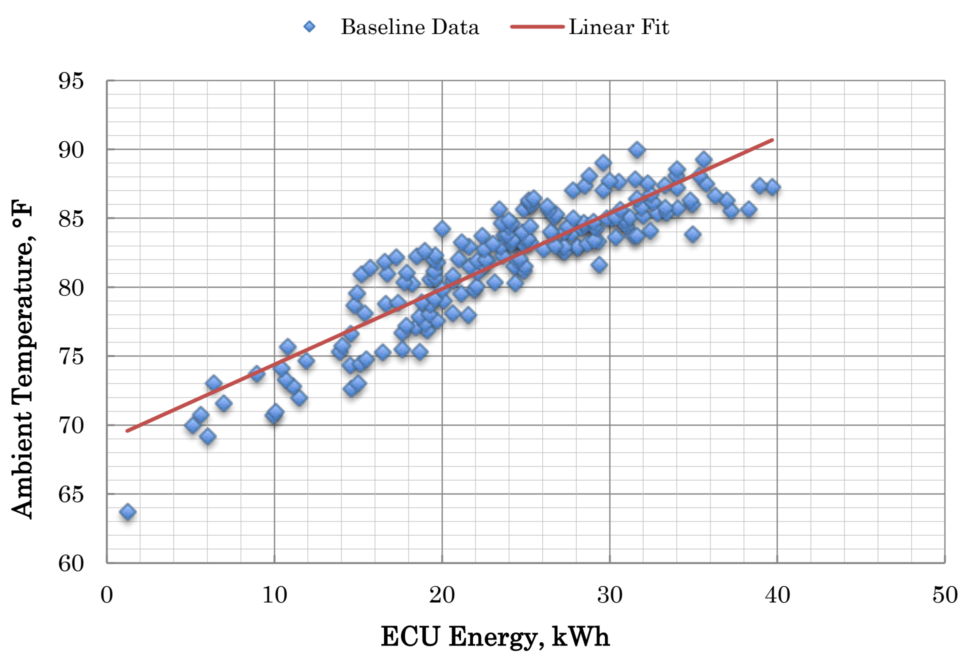


Figure 30: Baseline ECU Energy vs. Ambient Temperature

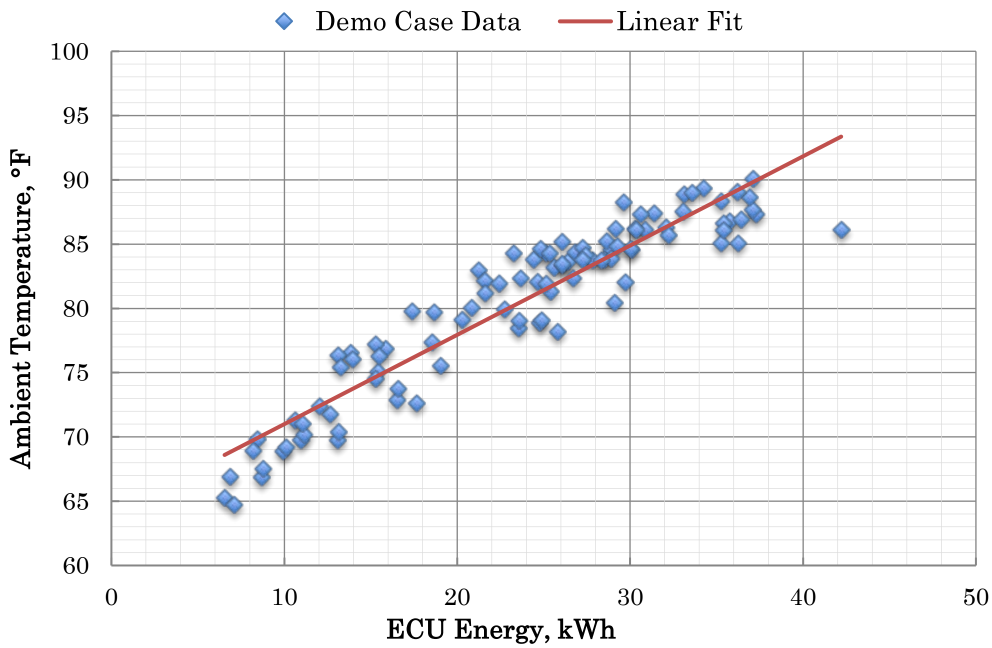


Figure 31: Retrofitted ECU Energy vs. Ambient Temperature

Cooling-degree days per day for the baseline ECU system were calculated for different number of days, specifically from 1 day to 7 days. Averaging over a number of days is used to smooth the data and provide better regression. Only results for Cooling-degree days per day for 1, 4 and 7 days are included in this report (the improvement in the R^2 value in other day averages were negligible). For the demo case, cooling-degree days per day were calculated for one-day interval. Using a one day base cooling degree days per day provides the most detailed behavior of the PCM retrofitted system.

6.1.3 Energy Savings

Using either model, baseline energy consumption can be predicted at the same weather conditions of the collected demo-case data. Energy savings can then be determined from the difference between the predicted (normalized) baseline energy and the actual demo case energy used for the desired number of days and the same cooling-degree days, specifically:

$$\Delta E = \frac{\sum_{i=1}^{N}\left(E_{Hd}(CDD_{di}, T_{soli}, H_{ri}) - E_i\right)}{\sum_{i=1}^{N} E_{Hd}(CDD_{di}, T_{soli}, H_{ri})} \qquad \text{Equation 18}$$

Where:

N = Usage number of days

ΔE = Total energy saving or loss

$E_{Hd}(CDD_{di}, T_{soli}, H_{ri})$ = Predicted baseline energy consumption at demo case conditions in i^{th}.

CDD_{di} = Demo case cooling degree-days per day in i^{th} day
T_{soli} = Demo case average sol-air temperature in i^{th} day
H_{ri} = Demo case average humidity ratio in i^{th} day
E_i = Total demo case ECU energy used in i^{th} day

6.2 CEILING COILS RESULTS

6.2.1 Model Parameters

Linear model results are based on cooling-degree days per day only, the nonlinear model accounts for solar air temperature, T_{sol} and humidity ratio, H_r. As expected, including the sol-air temperature and humidity ratio in the linear model produced inconsistent results due to significant collinearity between ambient temperature and both sol-air temperature and humidity ratio. The nonlinear model, on the other hand, produced consistent and stable results for all cases.

Linear Model Parameters

Linear model parameters, *a* and *b* in Equation 14, with the regression R^2 for 1, 4, and 7 days are shown in Table 7 and Table 8 for the baseline and demonstration cases respectively. Data for each averaging period and the corresponding line fits at 69 °F T_{BP} are shown in Figure 32.

Table 7: Baseline Linear Model Parameters

T_{BP} (°F)	Averaging Days	a	b	R^2
69	1	4.6685	1.47345	0.79
	4	4.7222	1.4693	0.87
	7	4.5032	1.4966	0.90

Table 8: Demonstration System Linear Model Parameters

T_{BP} (°F)	a	b	R^2
64	2.5583	1.272	0.88

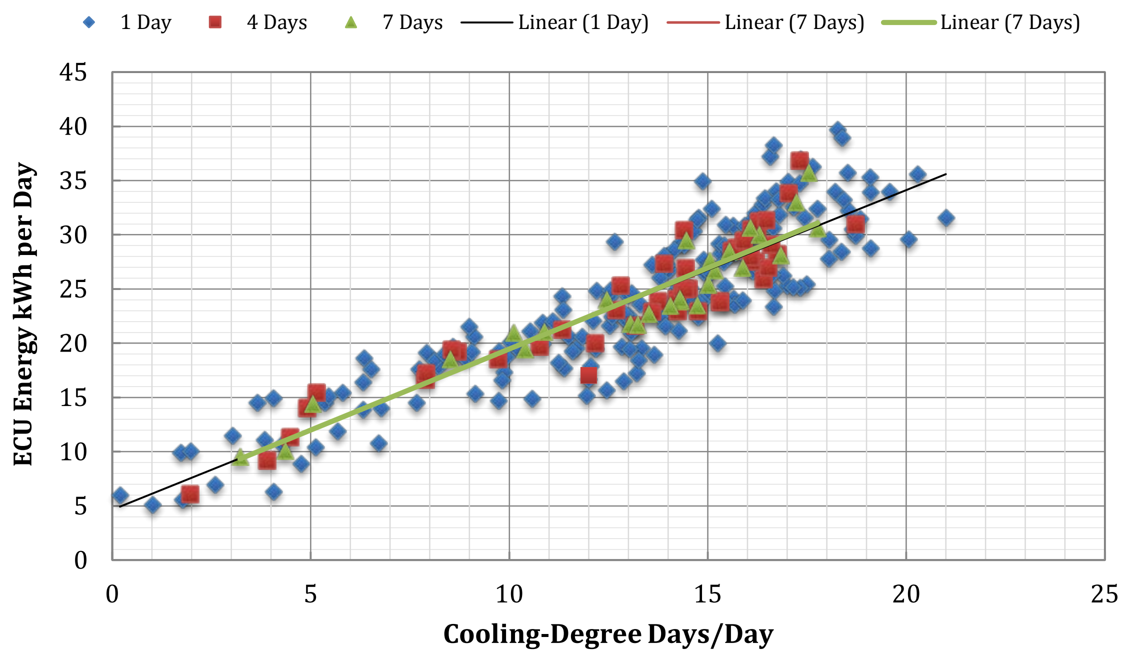


Figure 32: Baseline Energy Use Data

Nonlinear Model Parameters

Nonlinear model parameters, A, B, α and β, Equation 1, for the baseline case are shown in Table 9 and for the demo case in Table 10.

Table 9: Baseline Nonlinear Model Parameters

T_{BP} (°F)	Averaging Days	A	B	α	β	R^2
69	1	7.44923	0.00226666	1.51734	0.120363	0.81
	4	6.41627	0.00092192	1.52269	-0.115714	0.87
	7	5.89409	0.00070743	1.5238	-0.190381	0.90

Table 10: Demo System Nonlinear Model Parameters

T_{BP} (°F)	A	B	α	β	R^2
64	7.88354	0.0069782	1.50838	0.4714	0.90

6.2.2 Ceiling Coils Energy Savings

To compare the retrofitted ECU system energy consumption to the original system, baseline models were evaluated at the same weather conditions for the demo case data. The change in energy consumption is then calculated as:

$$\Delta E = (E_B - E_D) / E_B \quad \text{Equation 19}$$

where E_D is the demonstration case total energy consumption and E_B is the predicted baseline energy consumption over the same time period and weather conditions. Table 11 summarizes the percentage PCM retrofit energy savings for the linear and nonlinear models at 64°F T_{BP}. The average energy savings for each model are reported within the 90% confidence interval.

Table 11: Retrofit System Percentage Energy Savings

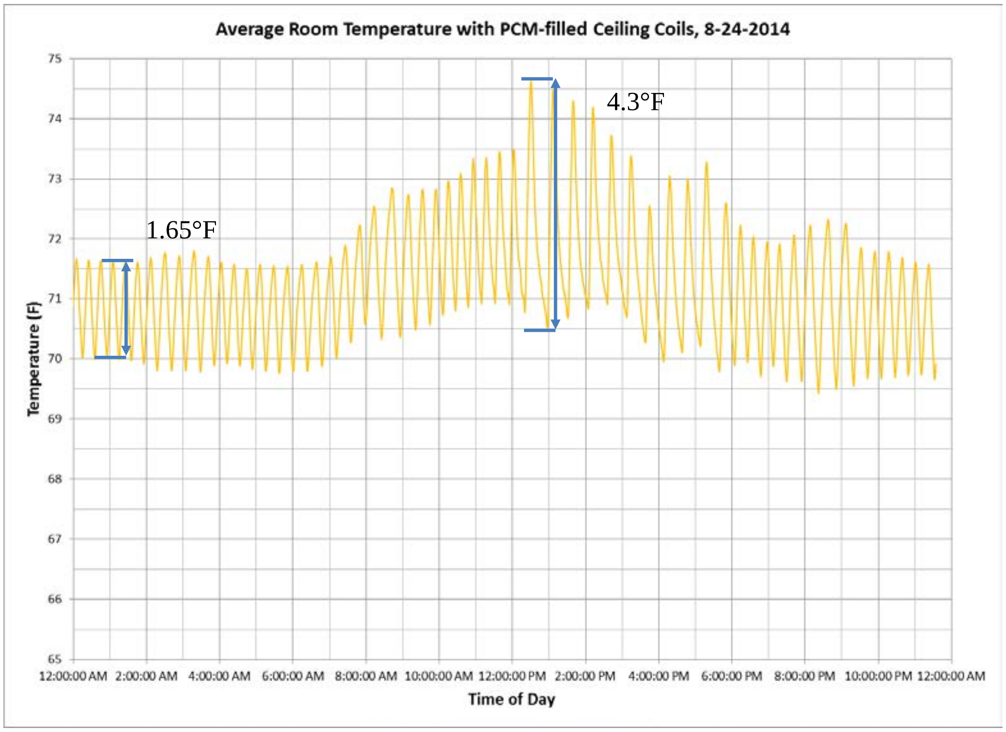
T_{BP} (°F)	Model	1 Day	4 Days	7 Days	Average Energy Savings
64	Linear	18.7519	18.7118	19.3557	18.9398 ± 0.7448
	Nonlinear	18.5443	19.8239	20.8602	19.7428 ± 2.3953

Here solar incidence and humidity influence is not profound (linear and nonlinear model results are essentially the same). This may be because weather conditions were not very different when the baseline and retrofit data were collected. It remains to be seen what impact these two parameters will have on the results when the nonlinear model is used at sites where the weather conditions, as far as solar incidence and humidity are concerned, are considerably different from one year to the other.

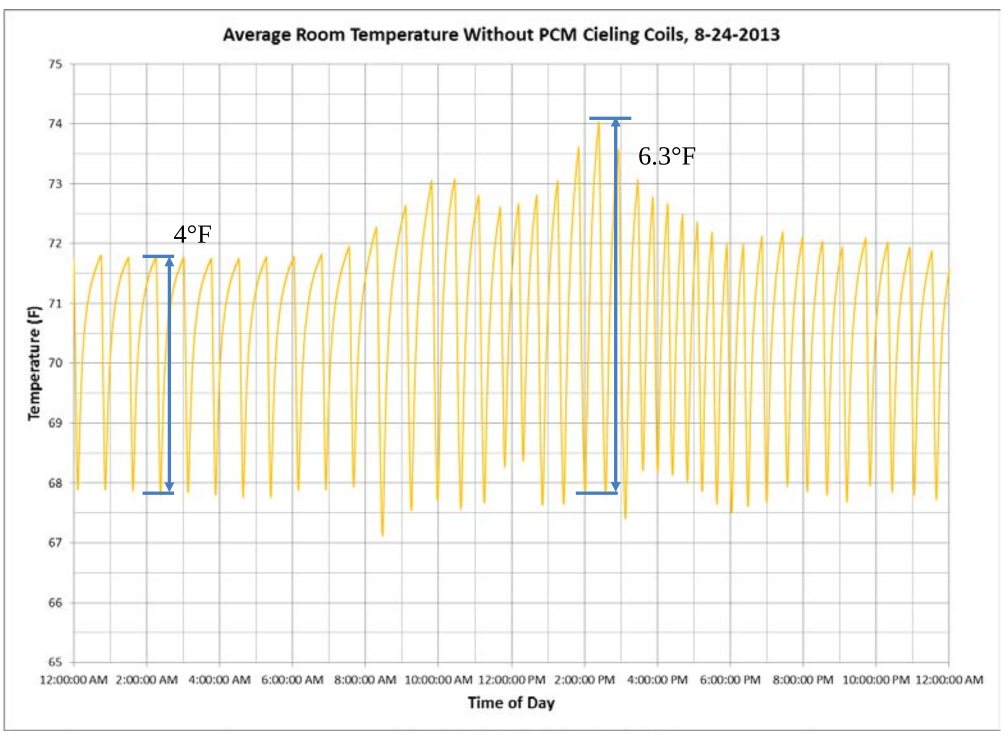
6.2.3 Room Temperature Regulation

Because latent heat is absorbed and released by PCM, the average room temperature fluctuated in a narrower band, when compared to the building configuration without the hybrid ECU system. Figure 33a and Figure 33b show the average room temperature with and without the PCM ceiling coils in place. The average was taken for 25 thermocouples hanged 9 feet above floor (3 feet below ceiling). The maximum room average temperature difference was 4.3°F for the PCM ceiling coils in place while it was 6.3°F for the baseline case. Also the minimum room average temperature difference was 1.65°F for the PCM ceiling coils in place while it was 4°F for the baseline case.

Narrow changes in temperature makes the room more comfortable than large temperature swings. Reducing the presence of low room temperatures points lead to the reduction of heat gained from the environment to the building interior. Figure 33 shows the lower room temperature ranged between 69.8°F and 70.5°F about 2 degrees higher than the baseline case.



(a)



(b)

Figure 33: Air temperature supplied to the room during demonstration (a) and during baseline testing (b).

6.2.4 Ceiling Coil Weather Dependence

PCM regeneration dependence on ambient temperature can cause suboptimal PCM use on hot days because the condenser unit must run frequently to cool the room. This is shown for a hot summer day in Figure 34 and Figure 35. As a result of frequent condenser unit cycling, PCM may change phase between condenser unit cycles at lower latent heat exchange with the room. Also, as shown in Figure 34 and Figure 35, PCM temperature decreased with the frequent condenser unit operation, but did not reach below solidification temperature of 57.2°F given in Figure 36.

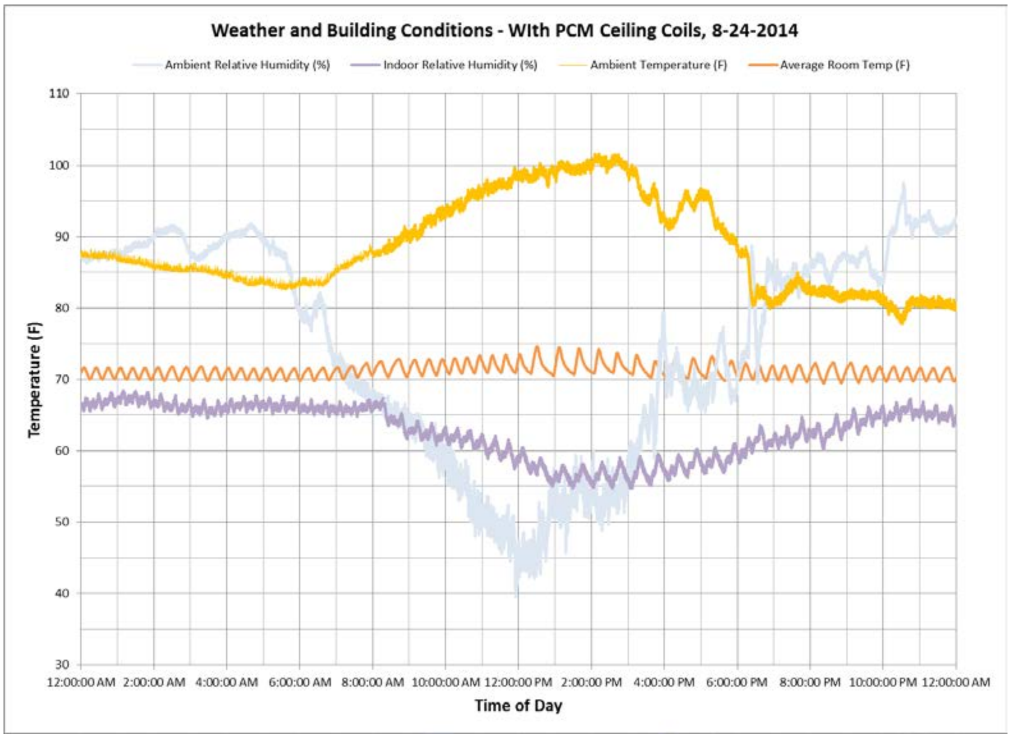


Figure 34: Ambient Temperature (Yellow), Ambient Relative Humidity (light Blue), Room Temperature (Orange), and Indoor Relative Humidity (Purple) For a Hot Day

To address these limitations and increase energy savings, a change in operation is needed. For example, in the current mode of operation, the ECU is the heart of the system, and the PCM coils supplement its operation. A better approach is to make PCM modules the main system component, where the ECU supplements PCM modules. In this mode, the thermostat would trigger the air handler fan only, allowing PCM coils to absorb heat from the room. Once the PCM is fully melted as indicated by PCM temperature, the condenser unit is activated until the PCM is fully regenerated. With this mode of operation, PCM temperature is always close to the phase change temperature, and the high latent heat capacity of PCM is better used.

In Figure 34 the room relative humidity was maintained as the ECU would maintain it, since the PCM ceiling coils are downstream of the ECU evaporator and the regeneration process depends solely on the ECU condenser unit operation. The relative humidity was maintained below the

ASHREA recommended level of 65% most of the day except during the early morning till around 8:30 AM.

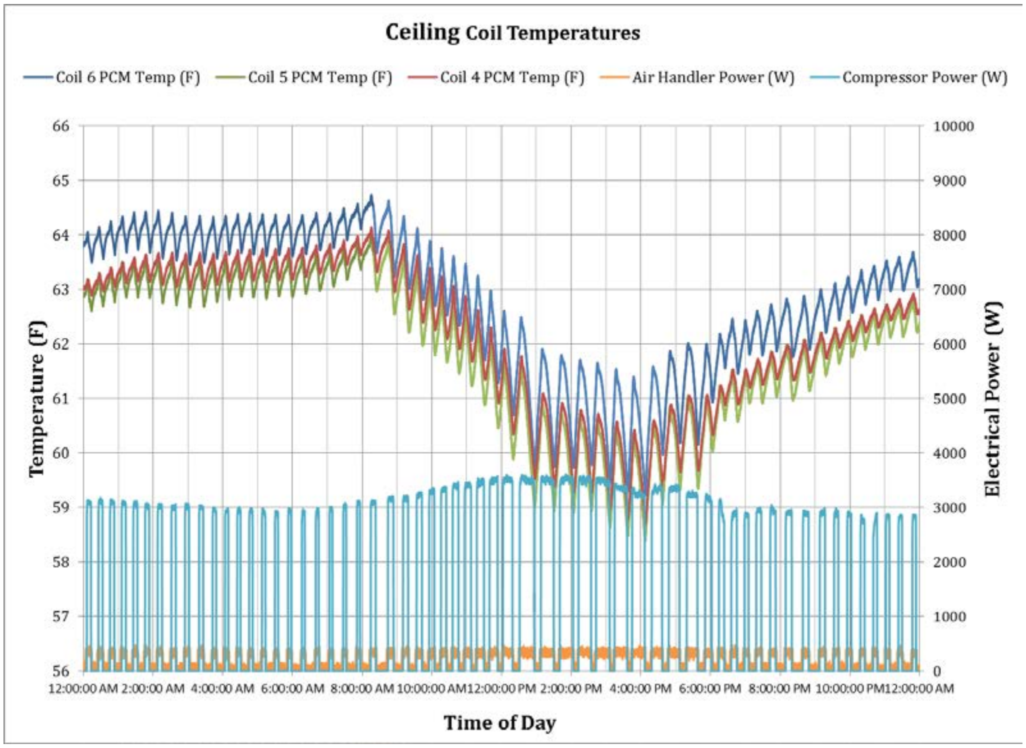


Figure 35: Coil 4, 5, and 6 PCM Temperature (Red, Green, Blue), condenser unit And Fan Power (Turquoise And Orange), and PCM Melting Point (Purple) For A Hot Day

6.2.5 Individual Ceiling Coil Performance

As shown above, ceiling coils achieved only about 19% energy savings when 30% was expected. A potential reason for this discrepancy could be that PCM in ceiling coils was not fully utilized, i.e. PCM was not totally melting and freezing. To determine the extent to which PCM in ceiling coils change phase, individual ceiling coil mass fraction is analyzed. Partial phase change impacts can then be quantified in terms of energy by examining individual ceiling coil's heat storage. The first step for determining mass fraction and heat transfer is to examine PCM properties in more detail.

PCM Properties for Mass Fraction and Heat Storage

PCM HSC varies as a function of temperature, Figure 36. Furthermore, the total amount of heat stored by the PCM is a function of its temperature change, and the range at which this change takes place. As stated in Equation 20, the change in enthalpy (Δh) for a specific temperature change $(\Delta T = T_2 - T_1)$ is the sum of the change in latent heat (Δh_{fs}) and sensible heat. In Equation 20 the average specific heat $(\overline{C_p})$ is calculated as a function of PCM mean temperature $((T_2 + T_1)/2)$.

$$\Delta h|_{T_1}^{T_2} = \Delta h_{fs}|_{T_1}^{T_2} + \overline{C_p}(T_2 - T_1) \qquad \text{Equation 20}$$

The experimental data illustrated in Figure 36 was used together with Equation 20 to calculate the latent heat change (Δh_{fs}) as a function of temperature.

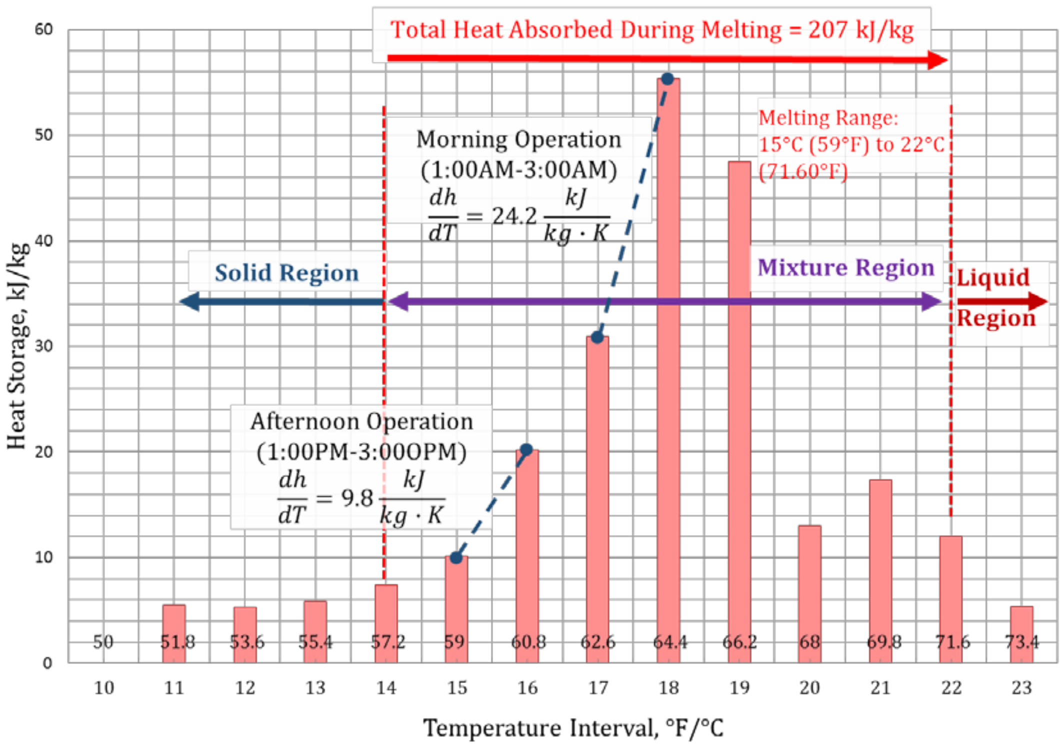


Figure 36: PCM heat storage capacity as a function of temperature. Solid, liquid and mixture regions and regions of operation during the morning and afternoon of August 24th 2014.

Ceiling Coil Mass Fraction

The relation between latent heat and the PCM temperature was used to formulate an expression for PCM solid mass fraction (X_s) as a function of PCM temperature. As stated in Equation 21, solid mass fraction can be calculated based on the latent heat stored from the onset temperature of phase change (T_L) and the PCM temperature (Ti), divided by the total latent heat of the material.

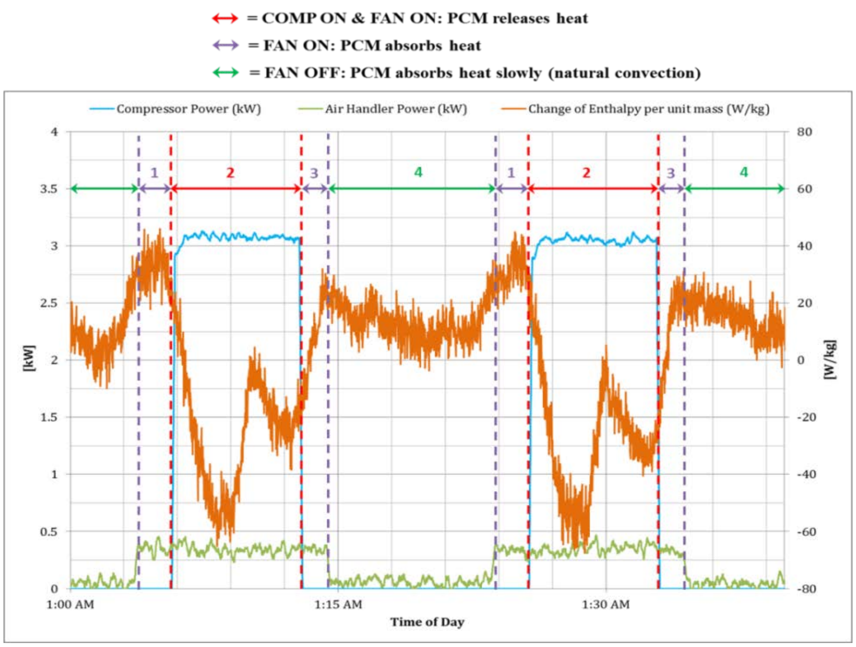
$$X_{s,i} = \frac{\Delta h|_{T_L}^{T_i}}{\Delta h_{fs}} \qquad \text{Equation 21}$$

The formulations presented in Equations 20 and 21 were used to analyze the PCM behavior under different ambient and operating conditions. First, PCM behavior was examined during individual condenser unit cycles from data collected on August 24th, 2014. Figure 37a shows PCM enthalpy change for two cycles from 1:00AM to 1:45:00AM. Air handler and condenser unit electrical power are presented in light blue and light green solid lines, and their values are indicated on the left vertical axis. These are included to indicate when each component is operating. PCM enthalpy change per unit mass is shown in orange on the right vertical axis. Each cycle can be broken down into four stages, labelled 1-4 in Figure 37a:

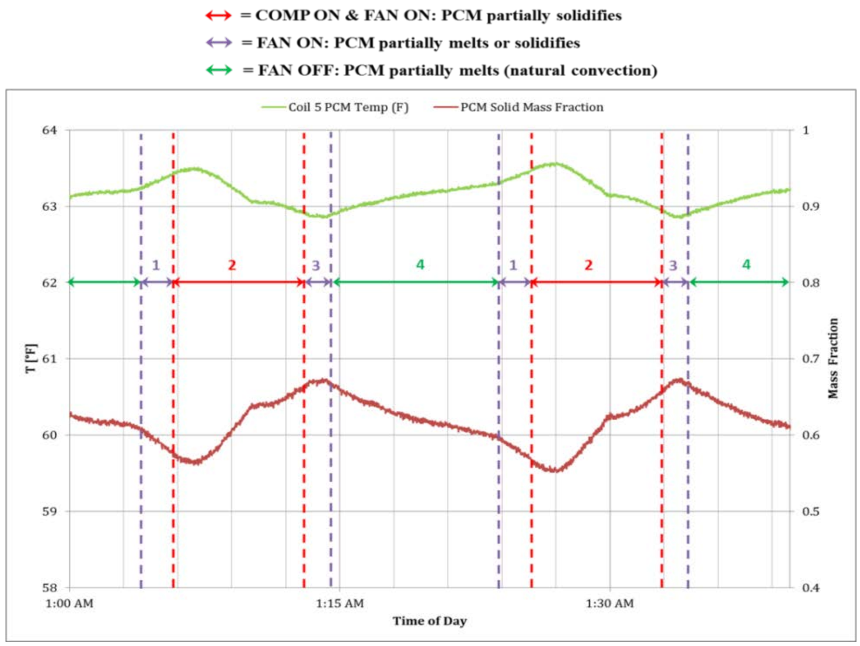
1. Fan turns on,
2. Condenser unit turns on,
3. Condenser unit turns off,
4. Fan turns off.

During the first stage, warm room air is circulated over ceiling coils, and PCM absorbs heat; enthalpy rate of change per unit mass is positive. In stage 2, the condenser unit turns on, supplying cold air to PCM, which releases heat leading to a negative PCM enthalpy rate of change. During stage 3, the condenser unit turns off and the fan continues to supply room air to the PCM. Initially, this air is cold due to the still cold evaporator coil, and the PCM releases heat. However, as the evaporator coil warms up and air temperature exceeds the PCM temperature, PCM absorbs heat. During stage 3, the enthalpy rate of change shifts from negative to positive. In stage 4, the fan turns off, and PCM absorbs heat from the room via natural convection; the enthalpy rate of change is positive.

As PCM absorbs or releases latent heat in each of the four stages, PCM solid mass fraction (X_s) changes as described in Equation 21. Figure 37b presents X_s and PCM internal temperature for the same period observed in Figure 37a. In Figure 37b, X_s oscillates around an average value of 0.62. The variation in the PCM's internal temperature shows the occurrence of semi-periodic partial solidification and partial melting processes. Hence, PCM was not used to its full potential in this cycle.



(a)



(b)

Figure 37: Condenser Unit Power and Rate of Change of Enthalpy (a) Temperature and Solid Mass Fraction Variation (b).

PCM behavior was also examined over the course of the day. Figure 38 presents the PCM temperature and PCM solid mass fraction from Figure 34b for the full 24-hour period. Of the stages previously described, stage 1 and 3 occurred for a fixed amount of time each cycle, but the length of stages 2 and 4 changes based on the heat pump's duty cycle, which increases or decreases due to ambient conditions. The impact of the heat pump's duty cycle on PCM solid mass fraction is evident in Figure 38. During the afternoon when the ambient temperature was higher, the heat pump's duty cycle increased; therefore, stage 2 becomes longer and stage 4 becomes shorter. As a result, the PCM spends total amount of heat released is greater than that absorbed ($h_f > h_m$), and the PCM solid mass fraction increases. Conversely, during early morning or late night hours, the heat pump duty cycle decreases, so stage 2 becomes shorter and stage 4 becomes longer. During these hours $h_f > h_m$ and the PCM solid mass fraction decreases.

In summary, under the conditions experienced during August 24th 2014, the state of the PCM was a mixture of solid and liquid phases, where two trends were observed. 1) local increase and decrease in PCM solid mass fraction on a per cycle basis, and 2) daily increase and decrease in PCM solid mass fraction resulting from changes in the heat pump's duty cycle.

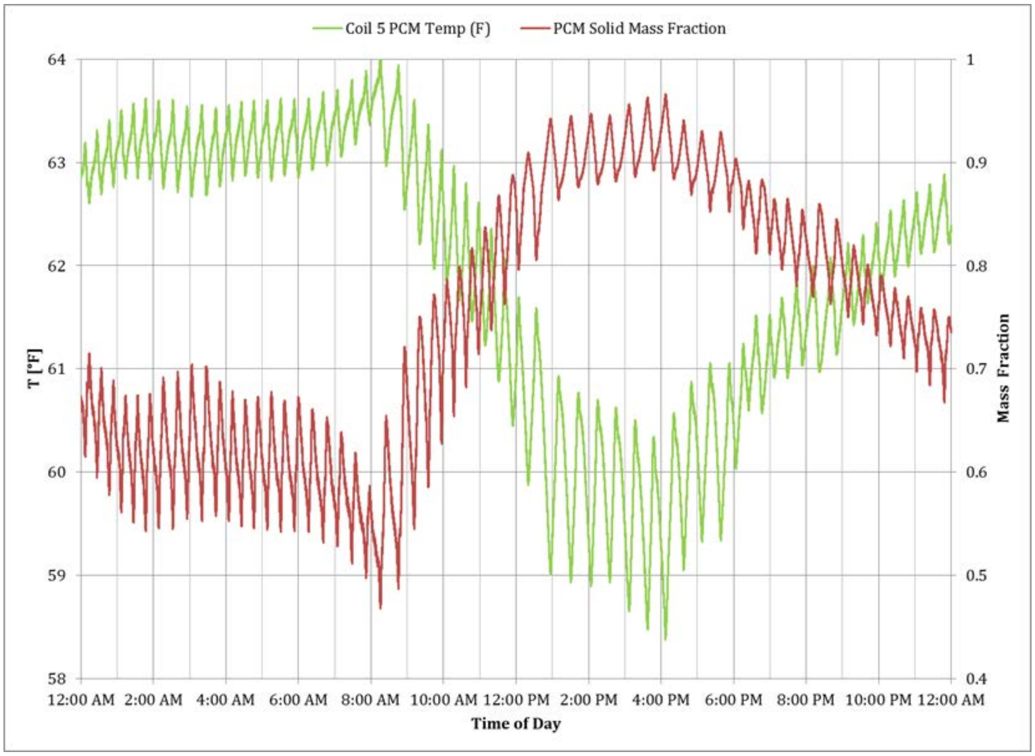


Figure 38: Temperature and Solid Mass Fraction Variation Over 24 Hours

Ceiling Coil Heat Transfer

Having determined that the PCM was not fully melting and freezing, we now needed to quantify these effects on energy storage performance.

The total heat dissipated or absorbed during partial freezing and melting cycles (h_s and h_m) was calculated as the integral of the change of PCM enthalpy with respect to time, as stated in Equations 22 and 23. Integration limits were defined as instances when local maxima and minima PCM temperature were recorded (t_{max} and t_{min}). For instance, total heat dissipated during a partial freezing event was calculated as the integral of latent enthalpy change between t_{min} and the immediately following t_{max}. The total heat absorbed during partial melting was calculated analogously, but the integration limits where from t_{max} to t_{min}.

$$h_m = \int_{t_{max}}^{t_{min}} \frac{dh_{fs}}{dt} dt \qquad \text{Equation 22}$$

$$h_s = \int_{t_{min}}^{t_{max}} \frac{dh_{fs}}{dt} dt \qquad \text{Equation 23}$$

The average amount of latent heat absorbed by the PCM during a partial melting process, taking place between 1:00 AM and 3:00AM, was calculated to equal 12.28 kJ/kg. Similarly, the average total latent heat dissipated during a partial freezing event occurring between 1:00AM and 3:00AM was calculated as 13.05 kJ/kg.

The methodology described by Equations 22-23 was also implemented for data recorded between 1:00PM and 3:00PM on August 24th 2014. Under these conditions, it was observed that the semi-periodic behavior of the ECU led to partial PCM freezing and melting events. It was also established that the ECU's duty cycle increased during the afternoon due to the increased heat load on the building. As a result the PCM internal temperature decreased while its solid mass fraction increased. Furthermore, the PCM consistently maintained a solid mass fraction greater than 0.95 due to its overall low temperature. The average latent heat absorbed during a partial meting process under the conditions experienced 1:00 PM and 3:00PM was 10.41 kJ/kg; while the average latent heat dissipated during partial freezing was equal to 11.3 kJ/kg.

A summary of the recorded conditions and calculated quantities during the morning and afternoon of August 24th are presented in Table 12. It was observed that the average maximum and minimum PCM temperatures (T_{max}, and T_{min}) were consistently higher between 1:00AM-3:00AM than during 1:00PM-3:00PM. On the other hand, the average temperature difference (ΔT) between T_{max} and T_{min} was larger in the afternoon than in the morning. This behavior was a consequence of the increased ECU's duty cycle during the afternoon. The time elapsed between partial melting and freezing (Δt_m, and Δt_f) was calculated as the time between the PCM temperature's local minima and maxima. It was observed that Δt_m is larger during the morning than in the afternoon; and that Δt_f is significantly longer in the afternoon.

Table 12: PCM Temperatures and Performance Quantities

August 24th 2014.		
Quantity/ Units	1:00AM-3:00AM	1:00PM-3:00PM
T_{max}, °F/°C	63.58/17.54	60.76/15.98
T_{min}, °F/°C	62.79 /17.11	58.94/14.97
ΔT, °F/°C	0.79/0.44	1.82/1.01
Δt_m, min	14.03	11.73
Δt_f, min	7.59	20.89
H_m, kJ/kg	12.29	10.41
H_f, kJ/kg	13.05	11.27

The average h_f and h_m are also summarized in Table 12. The partial freezing and melting cycles occurring during the morning of August 24th 2014 dissipated and absorbed more energy than those occurring in the afternoon, despite ΔT was larger in the afternoon than in the morning. Such behavior was caused by the dependence between latent heat storage capacity and PCM temperature. Figure 36 illustrates the measured heat storage capacity as a discrete function of PCM temperature. Solid, liquid and solid+liquid (mixture) regions are also defined in Figure 36, and the total heat absorbed during phase change is stated. Furthermore, the temperature range over which the PCM operates during the morning and afternoon are illustrated using blue dashed straight lines. As shown in Figure 36, the change of PCM temperature occurring between 59°F (15°C) and 60.8°F (16°C) leads to a smaller amount of energy dissipated or absorbed than one taking place between 62.6°F (15°C) and 64.4°F (18°C).

6.3 PEAK LOAD SHAVING RESULTS

As stated before, the PLS coil was selected to cover only 2 hours of the 6 hours period due to the size of the PLS coil and the space availability in the demonstration site. The results of the 2 hours could then extrapolated to cover the 6 hours peak load period. Section 7.1.2 calculated the energy savings for the 2 hours PLS and extended the analyses to cover an ideal case that covers the 6 hours peak load period. In Table 15, for the 2 hours PLS, the energy savings were 1.47% while energy cost showed 6.2% reduction. In Table 16, for the full 6 hours PLS, the energy savings were 5.33% while energy cost showed 20.88% reduction.

6.3.1 Closed Loop Regeneration

Figure 39 shows room temperature and average indoor relative on the left vertical axis. This figure shows electrical power usage of the condenser unit and air handler on the right vertical axis. Based on Figure 39's data, the PLS coil was able to maintain room temperature for about two hours from a one-hour charge. Specifically, the unit was regenerated from 5:00-6:00 AM (period of constant condenser unit and fan operation) and the condenser unit remained unused from 1:00-3:00 PM (condenser unit power is zero) while the room temperature was maintained at its set point. Since the condenser unit power usage is highly correlated with outdoor temperatures, this shift in condenser unit usage time resulted in energy savings. Further, higher electrical rates during peak hours are avoided. Continuously running the fan during PLS coil melting lead to an increase in average relative indoor humidity. This may be an issue needing resolution at a later time.

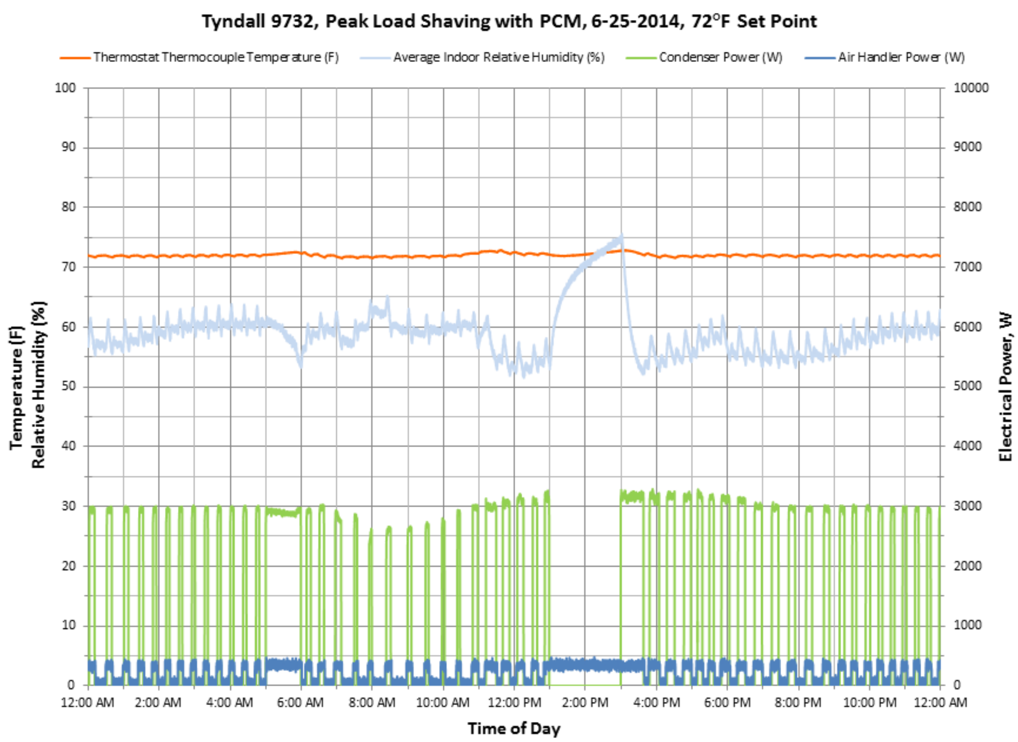
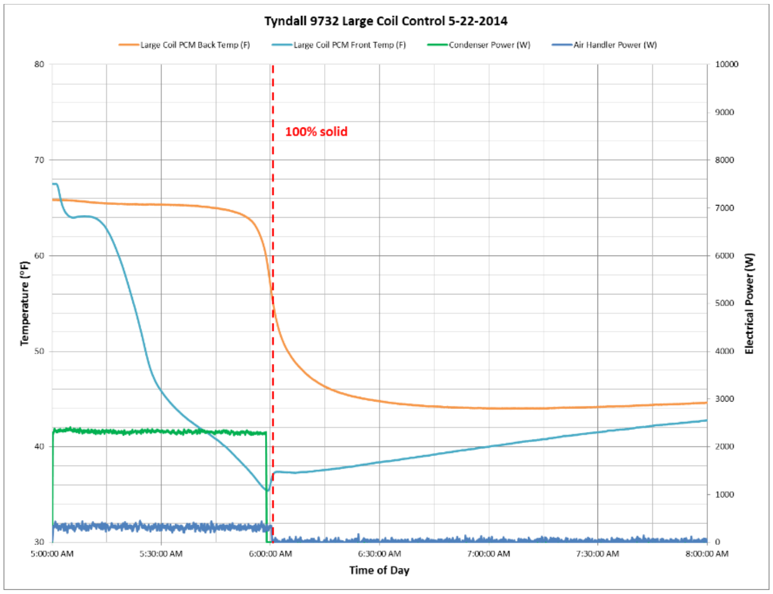


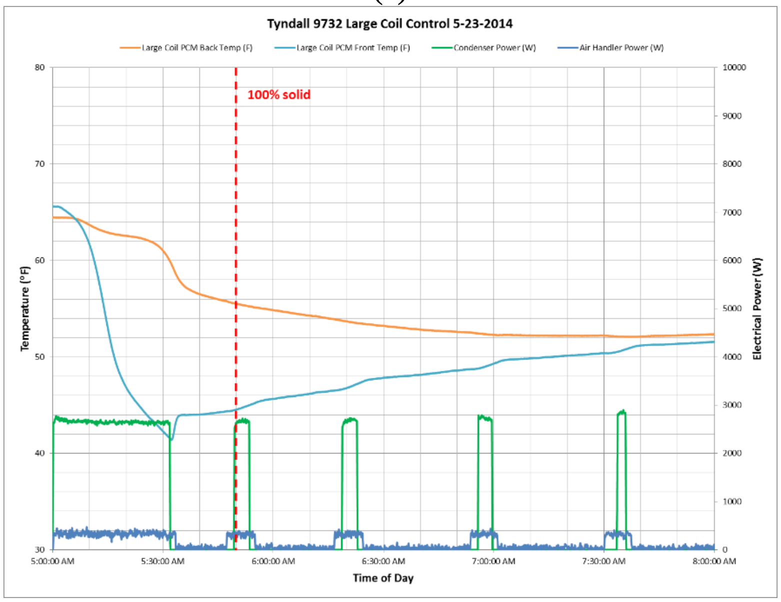
Figure 39: Peak Load Shaving Using Closed Loop Regeneration

PCM Regeneration – Peak Load Shaving Demonstration

To improve future designs and controls, the phase change process within the coil was examined in detail. Phase change progresses from the inlet to the exit of the PCM module, consistent with the direction of airflow. As PCM at the inlet changes phase, it transfers heat to the air, changing the air temperature that reaches PCM further downstream. Thus PCM in the coil's last tube row is last to change phase, and can be used as an indicator that all PCM has changed phase. Complete freezing time varied from day to day (vertical red line Figure 40), depending on the PCM's initial temperature and mass fraction. On May 22, 2014 PCM was fully frozen slightly after 6:00:00 AM; on May 23, 2014 it was fully frozen at about 5:50:00 AM.



(a)



(b)

Figure 40: Closed Loop Solidification on (a) May 22 and (b) May 23, 2014

In addition to showing the fluctuating solidification times, Figure 40 demonstrates two other important PCM behaviors:

1) When PCM has solidified, there is an abrupt decrease in PCM temperature. This can be seen by examining the back PCM temperature (orange) at 6:00 AM, Figure 40a, and 5:30 AM, Figure 40b.
2) When closed loop freezing ends, the back PCM temperature continues to decrease even though no air flows through the PCM unit. Since the front PCM temperature is substantially lower, the back PCM temperature continues to drop as temperature throughout the PLS coil equilibrates.

These behaviors show that to solidify PCM with minimal condenser unit operation, the condenser unit should be disengaged early so that thermal inertia completes the freezing operation. We experimented with different back PCM temperature thresholds to optimize condenser unit operation. In Figure 40 the condenser unit was disengaged when the back PCM temperature reached 60°F. However, when PCM temperature equilibrated, it was in the low 50's or 40's °F, showing that the condenser unit operated longer than required to guarantee complete solidification. We gradually increased the back PCM temperature requirement until June 25, 2014, Figure 41, to eliminate wasteful condenser unit operation.

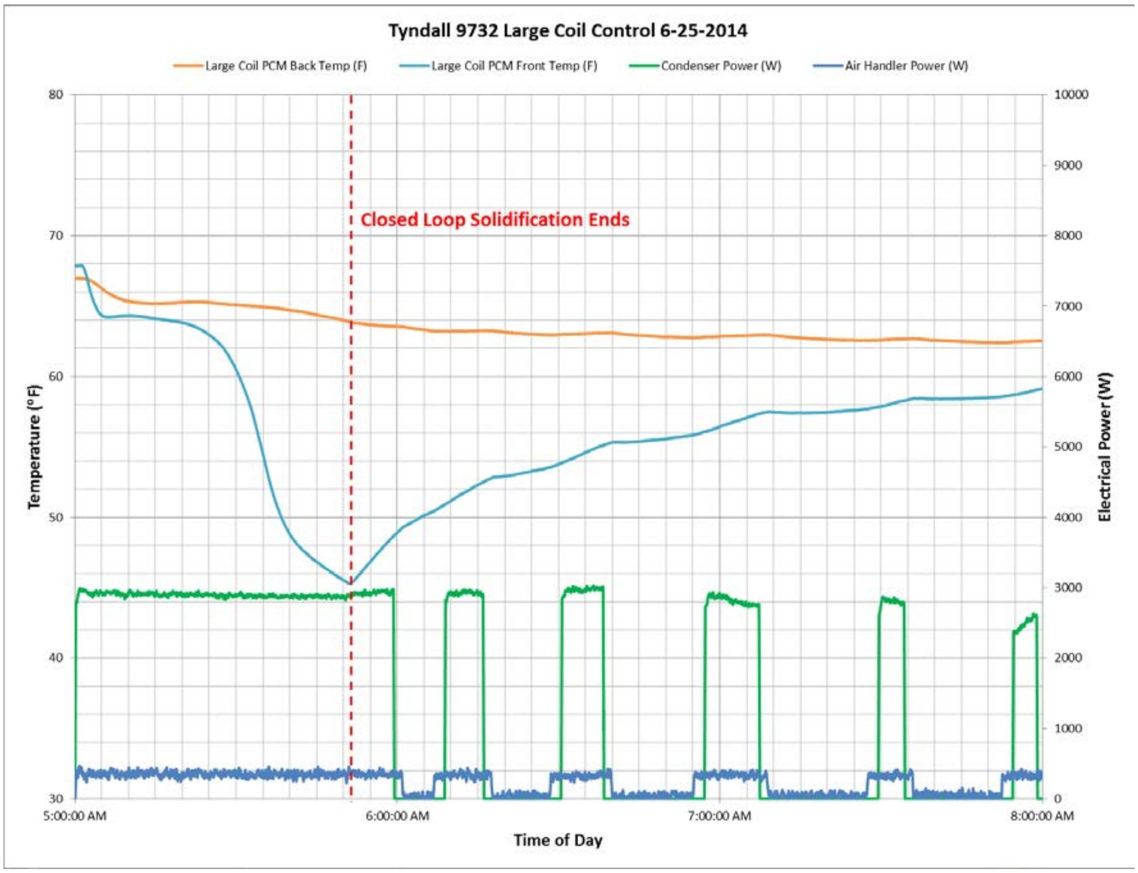


Figure 41: Closed Loop Solidification on June 25, 2014

In the above test, Figure 41, closed loop solidification ended at approximately 5:50 AM. At this point, airflow stopped following to the PCM unit, and the ECU cooled the room instead. The same thermal inertia is present in this run as in Figure 40b. However, PCM temperatures did not equilibrate in the 50's or 40's °F. While the PCM temperature suggests the back PCM might not been 100% solidified, it should have been mostly solidified based on previous experimentation, and the majority of wasteful condenser unit operation was eliminated.

PCM Melting – Peak Load Shaving Demonstration

On June 25, 2014, PCM started melting to cool the room at 1:00:00 PM and maintained the room temperature until 3:00:00 PM, Figure 42. At 3:00 PM, the PCM temperature at the front and back of the unit was 24°C (75.3°F) and 18.9°C (66°F) respectively. Figure 36 shows, in Q18 melting, heat absorbed above 19°C (66.20°F) is small as melting is almost complete. Therefore, almost all PCM capacity was used to cool the room, and the melting operation was close to optimal.

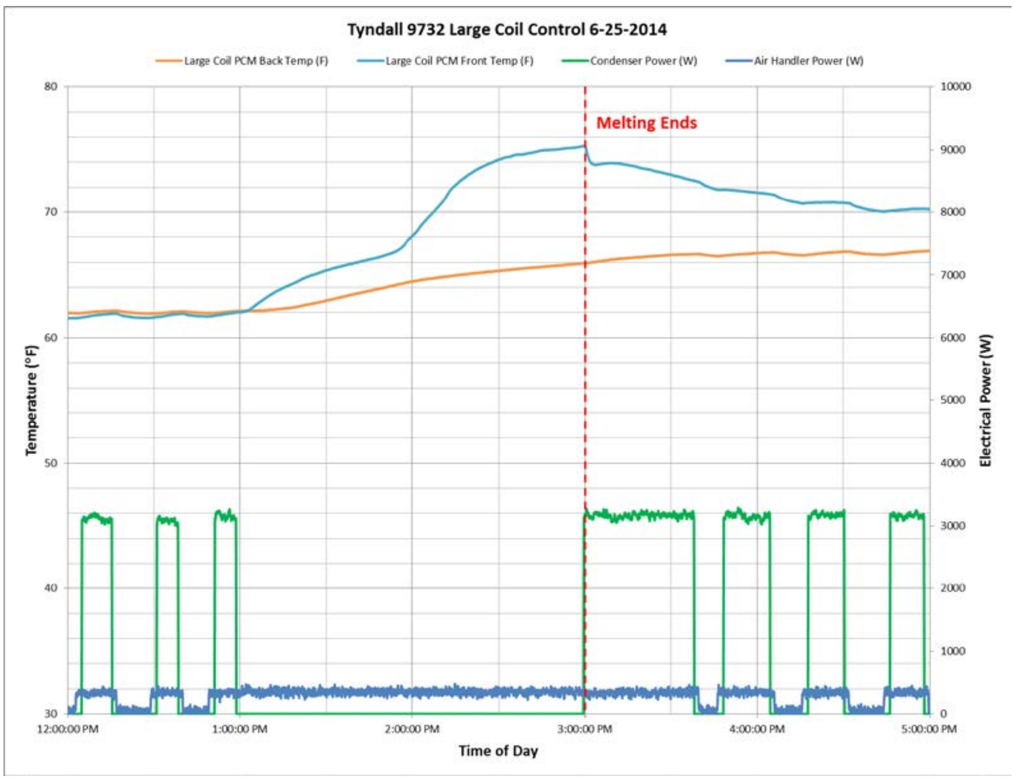


Figure 42: Melting on June 25, 2014

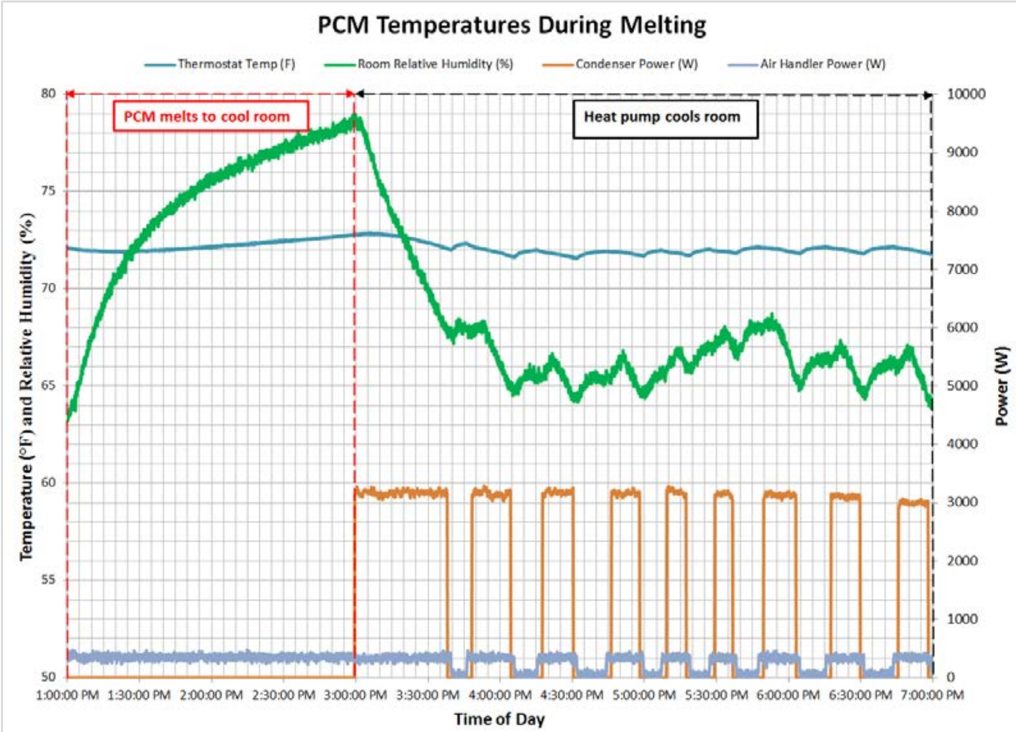


Figure 43: Room Relative Humidity During Melting

Immediately following PLS, the first condenser unit cycle appears longer than normal, Figure 42 and Figure 43. This is most likely due to the increase in humidity in the room during the melting portion of the test. Figure 43 also shows the temporary increase in the relative humidity of the room during melting and the reduction in relative humidity by the ECU during the next condenser unit cycle.

In Figure 43, the relative humidity in the room (green line) increased from 63% to 78% during the melting period. When PCM fully melted and could not cool the room, the thermostat triggered the condenser unit to start, this occurred at 3:00:00PM. During the first condenser unit cycle, it must cool the room while reducing the relative humidity. In Figure 43, the condenser unit returns relative humidity to the buildings' precondition state during the first condenser unit cycle.

It is worth noting that the high relative humidity during PCM melting period is due to two factors: 1) the demonstration site's geographic location, so the effect may not be present in climates with lower humidity; and 2) The PCM melting point is higher than the room dew point preventing air humidity from condensing in the PLS coil.

The demonstration showed the PCM can maintain room temperature in the range of 71-73^{o}F during the peak hours. The increase in relative humidity is because the building is located in high humidity climates where ambient humidity stayed in above 75%. At room temperature of 72^{o}F and 60% relative humidity the air dew point is 52.18^{o}F, to reduce the relative humidity to proper levels, a PCM material could be chosen with a lower melting temperature than the air dew point to condense the water from the humid air. At 78^{o}F, the room temperature mandated by the DOD, and 60% relative humidity the air dew point is 63^{o}F. The PCM used in this demonstration, with melting

temperature of 64.4°F should be able to condense room air humidity and maintain the relative humidity at 60-65%.

Losses while Idle between Solidification and Melting – PLS Demonstration

Since PCM temperature measurements could only be taken at the PLS coil's front and back, temperature distribution in the PLS coil's middle must be estimated to calculate total heat stored or released over a time interval. If phase change is involved, this estimation can have a large impact as the material stores substantially more heat per degree temperature change. Therefore, a test was conducted using 60°F as a freezing threshold temperature to ensure the PLS coil was completely frozen.

On May 22, 2014, Figure 44, the average PCM temperature at front and back of the unit was 1.9°C (35.4°F) and 11.9°C (53.4°F) when the closed loop solidification operation ended. The back temperatures then decreased and the front increased as PCM temperatures equilibrated. At the end of the idle period, the average PCM temperature at the front and back of the unit was 12.2°C (54°F) and 10.89°C (51.6°F).

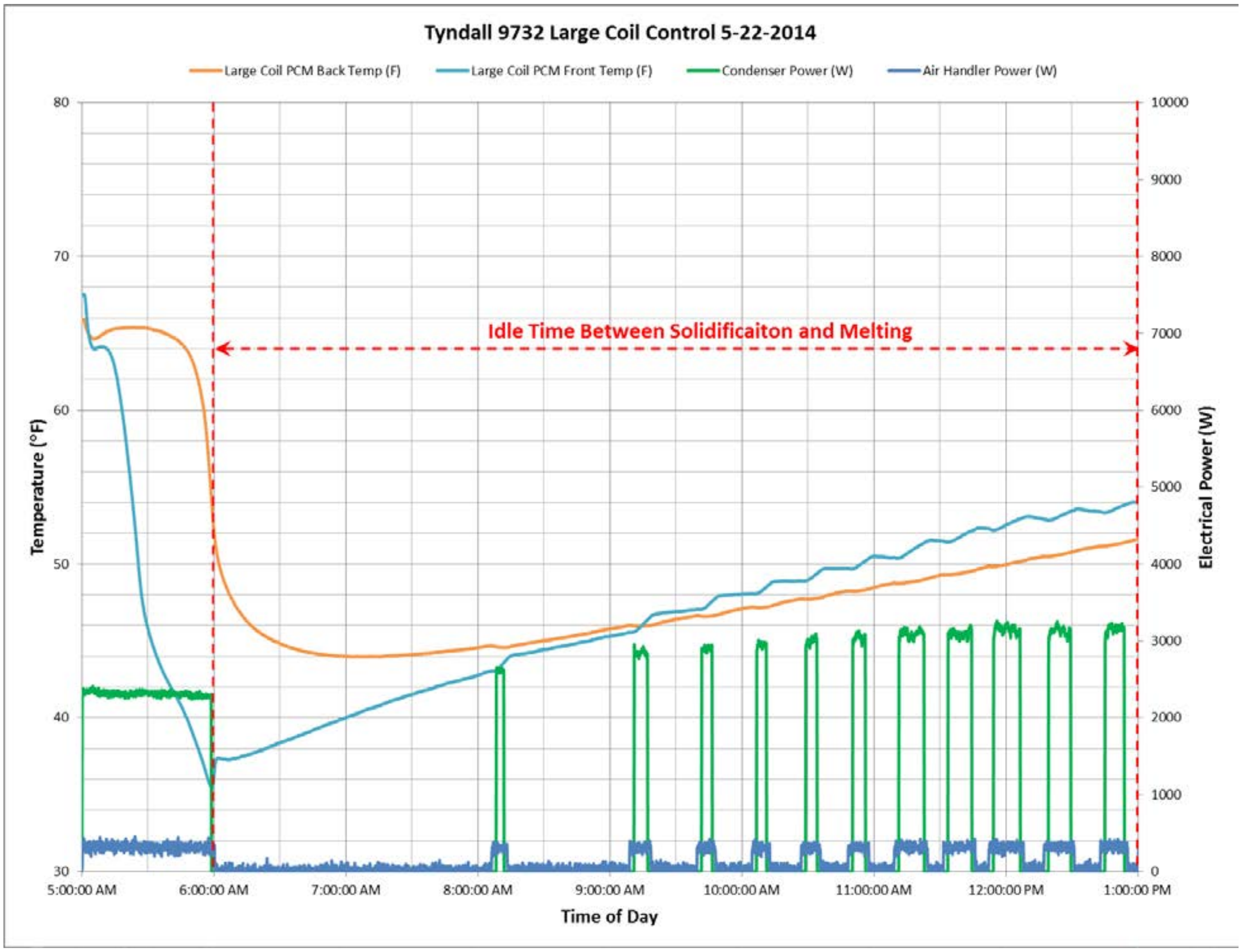


Figure 44: Average PCM Temperature at the Front and Back of the PCM Unit While Idle Between Solidification and Melting.

Figure 3 indicated the onset of Q18 melting is 14°C (57.2°F); since the front and back PCM temperatures were below this threshold for the entire interval, it was assumed that all PCM was solid for this portion of the day. Therefore, all heat gain from the room over this interval was manifested as a PCM temperature increase. Assuming no phase change, a linear approximation was used to estimate PCM temperature distribution between the front and back of the unit, Figure 45. Losses, or heat gains from the room, are determined by calculating the PCM heat gain during the time interval.

Figure 45's PCM temperature distribution was used along with the total heat stored at each PCM temperature (Figure 3) to calculate PCM total heat storage at the start and end of the time interval. The difference between the final heat storage and initial heat storage is the PCM heat gain, which is 3,385 kJ for this interval on May 22, 2014. Based on the PLS coil's anticipated heat storage capacity of 28,500 kJ during phase change, and the fact that on June 25, 2014, the PCM temperatures were higher during this interval, we can assume that *less than* 3,385 kJ or 10% capacity was lost due to heat gain from the room.

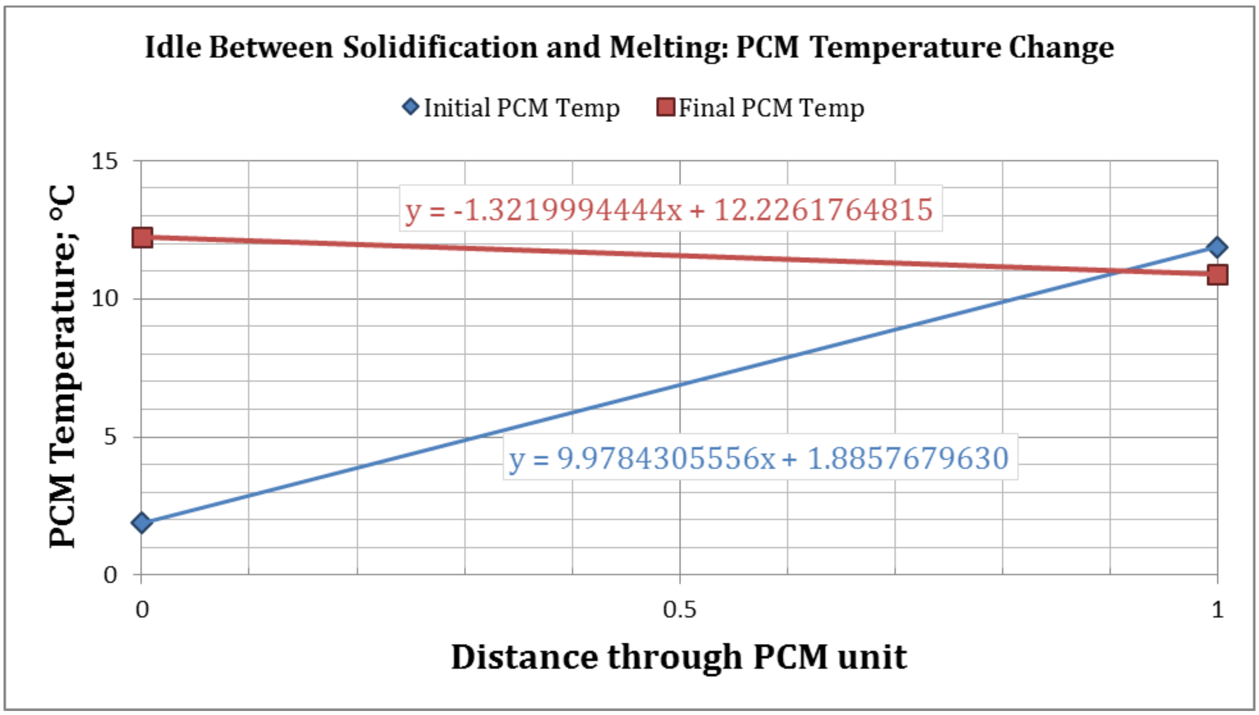


Figure 45: Assumed Linear PCM Temperature Distribution at the Start and End of the Idle Period Between Solidification and Melting. Linear Assumption is Based on Low PCM temperatures, Indicating No Phase Change.

6.3.2 Open Loop Regeneration

In this configuration, air always routed through the PCM module into the room. Figure 46 shows results from this operation mode. During testing, this method was used to freeze PCM and resulted in a long condenser unit cycle at 2:20:00PM immediately following melting. This cycle was long because the ECU had to cool the room, reduce humidity, and solidify the PCM at the same time. Because the peak period covered was short; this operation mode showed the long condenser unit

cycle occurred during peak hours. However, in an ideal case, the PCM module would cool the room for the full peak period and the long condenser unit cycle would occur immediately after off-peak hours. While reducing system complexity, this approach does not allow regeneration to occur during the time of day where ambient temperatures are cooler and condenser unit power consumption are at a minimum as in the closed loop regeneration case, so it is not as energy efficient as the closed loop regeneration method.

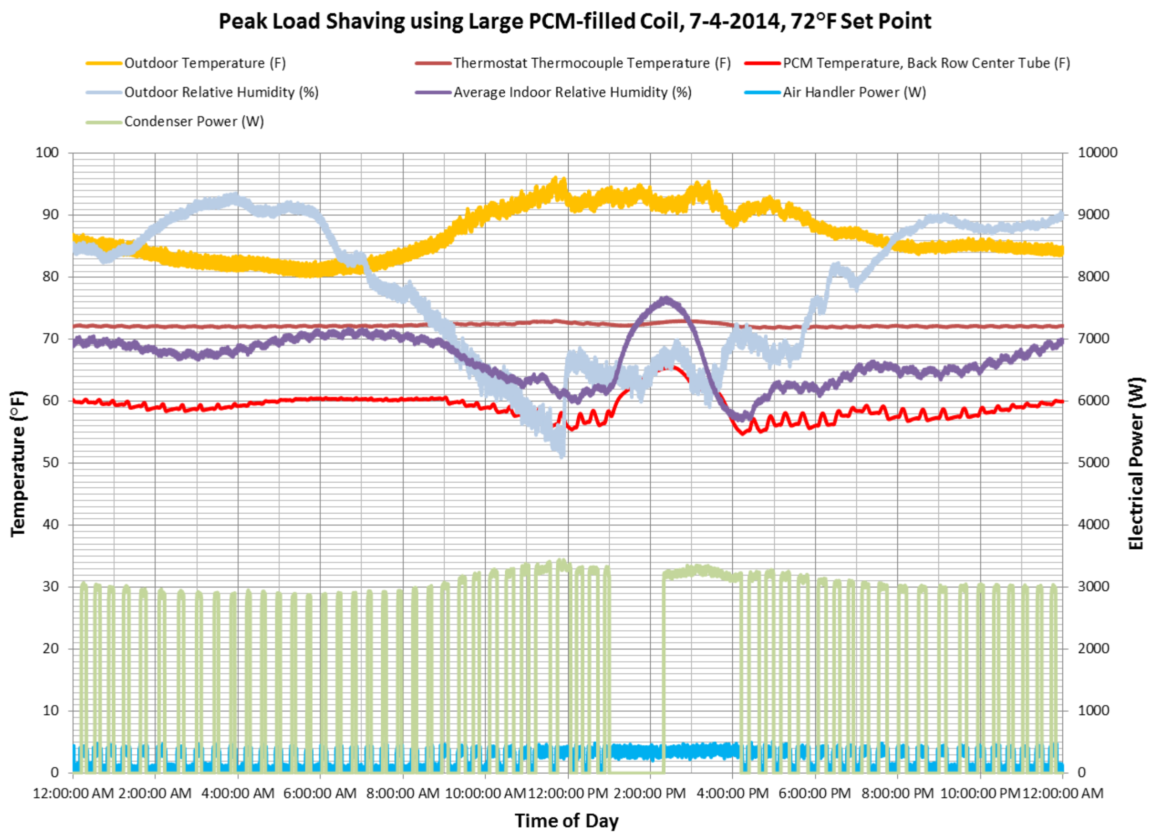


Figure 46: Peak Load Shaving Without Closed Loop Regeneration

6.4 PERFORMANCE BASED CONCLUSIONS AND RECOMMENDATIONS

6.4.1 Ceiling Coil Recommendations

A limitation of the PCM-filled ceiling coil application is the low flow rate at the registers. Ideally, the PCM would change phase completely each cycle, melting to absorb heat from the room and regenerated by the condenser unit. There are two possibilities for improving the flow rate to registers. The first is to replace the air handler fan with one that provides a higher flow rate. This approach has its own limitation, since the increase in flow rate adversely affects the energy use by the Hybrid ECU. The second is to redesign the PCM module for a better heat transfer rate.

6.4.2 Peak Load Shaving Recommendations

Capacity and Controls Adjustment

In an ideal case for June 25, 2014, Figure 42, PCM would have melted in six hours, eliminating condenser unit activity for the entire peak period. However, three times the PCM mass would be required. To adjust for the additional PCM mass, the closed loop's freezing period should also be increased to 1.5 hours. Using these changes, an ideal day can be constructed from existing demonstration data using the following modifications:

1. The charging period should be extended to 1.5 hours, where the air handler and condenser unit loads are modified.
2. The 6-hour peak-load period should be modified so that the fan runs continuously, and the condenser unit does not run at all.
3. The hour immediately following the PCM melting period should be modified as a catch up hour, where the ECU returns the relative humidity in the room to normal levels. During this hour, the fan and condenser unit run continuously. This is a conservative adjustment, since the relative humidity in the room was returned to normal in 30 minutes during the demonstration.
4. The hour immediately following the regeneration period should be conservatively modified as a catch up hour for room temperature, since the gym is not conditioned during closed loop regeneration. This adjustment can be made by adding the energy the ECU unit would have used to condition the building during the regeneration (according to the baseline) to the hour immediately after charging.

To improve the above adjustments' accuracy, change in condenser unit power consumption as a function of ambient temperature should be included. In the condenser unit, the power consumption has a strong linear correlation with ambient temperature; it uses more power during higher ambient temperatures. This relationship was characterized for the ECU in the demonstration building during steady state operation, covering a range of ambient temperatures between 60°F and 100°F, Figure 47.

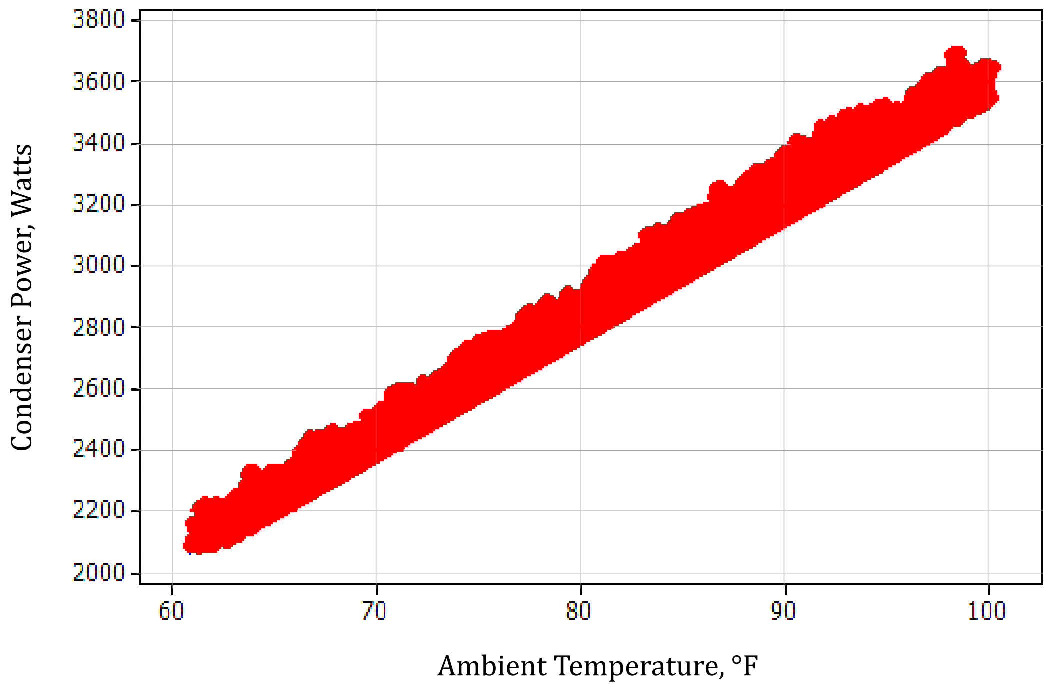


Figure 47: Condenser unit Power as a Function of Ambient Temperature

The equation for the graph in Figure 47 has an R^2 value of 0.985, and is given as:

Condenser Power = – 302 + 28.8 T_{amb} Equation 24

This relationship is important in the PLS analysis, as condenser operation is moved from peak hours with high ambient temperatures to off peak hours with lower ambient temperatures. For example, if it is 90°F outside, the condenser can be expected to use 3,190 watts. However, if this operation is shifted to a time of day where it is only 70°F outside, the condenser can be expected to use only 2,414 watts, a 32% reduction in energy use. With Equation 24, the maximum ECU energy for a given hour can be determined knowing that hour's ambient temperature.

Using Improved Materials

In this demonstration, we used the materials and manufacturing capabilities available at the time of the design efforts. For the PCM, we used the Q18, which is made of vegetable oils, has melting range extends from 14°C (57.2°F) to 22°C (71.60°F) with a melting point at 18°C (64.40F) and 207 kJ/kg latent heat. The PCM module design used the tube and fin air-to-PCM heat exchanger design. These factors resulted in a large PLS coil. Since the PLS coil's current size and footprint could hinder the wide commercialization of the technology, the ESTCP committee, during the ESTCP In-Progress Review meeting of fall 2014, requested ARA to address the size and footprint of the PCM system and develop strategies for reducing them. Addressing these factors resulted in the following:

1. PCM Specific Latent Heat – Using PCM with higher specific latent heat will result in a smaller PLS coil's footprint. Some PCMs have higher latent heat but lower density resulting in an increase of the footprint of the PLS coil. For example, hexadecane, which

has a melting point of 18°C (64.4°F) and 230kJ/kg latent heat, its density is 770 kg/m^3, making its energy density 177,100 kJ/m^3. Q18 has the same melting point, 207 kJ/kg latent heat, and 815 kg/m^3 density, making its energy density 168,705 kJ/m^3. Using hexadecane the reduction in volume is about 5%. Kaplan PCM 11 has 13°C (55.4°F) melting point, 320 kJ/kg latent heat, and 773 kg/m^3 density making its energy density 247,360 kJ/m^3. Using Kaplan PCM 11 will result in a volume reduction of 46.62%.

2. PCM Melting Point – At a room set point of 72°F and 65% RH, the dew point is 59.6°F, so current and proposed PCM, except Kaplan PCM 11, do not provide dehumidification under these conditions and room RH will rise above 65%. Unless the PCM temperature gets below the dew point, no dehumidification will occur. However, at room set point of 78°F and 63% RH the dew point is 64.4°F and the PCM module will provide air dehumidification making the 63% RH the higher limit of RH in the room.
3. PCM Module Design – The current PCM module is a fin-and-tube design. It is made using 1" circular tubes with 12 fins per inch. Brazing thin aluminum fins to flattened aluminum tubes produces compact and efficient heat exchanger. We investigated the use of flat tube and our calculation showed a reduction in the PCM module volume by 20%. Therefore, instead of using tube and fin air-to-PCM heat exchanger design, a different type of heat exchanger called bar-and-plate design can be used. The bar-and-plate design results in flat tube configuration with fins on the inside of the tube and in between tubes. This approach will make the PCM module smaller in size, lighter in weight, and with high heat transfer coefficient.
4. To address these limitations and increase energy savings, a change in the mode of operation is needed. For example, in the current mode of operation, the ECU is the heart of the system, and the PCM modules supplement its operation. A better approach is to make the PCM modules the main system component, where the ECU supplements the PCM modules. In this mode, the thermostat would trigger the air handler fan only, allowing the PCM coils to absorb heat from the room. Once the PCM is fully melted as indicated by PCM temperature, the condenser unit is activated until the PCM is fully regenerated. With this mode of operation, PCM temperature is always close to the phase change temperature, and the high latent heat capacity of PCM is better used.
5. In Figure 34 and Figure 35, the room relative humidity was maintained as the ECU would maintain it, since the PCM ceiling coils are downstream of the ECU evaporator and the regeneration process depends solely on the ECU condenser unit operation. The relative humidity was maintained below the ASHREA recommended level of 65% most of the day except during the morning till around 8:30 AM.

6.4.3 Recommendations for Both Technologies

As test data show, both technologies have shown level of success in reducing energy consumption and increased energy cost savings as applied to the demonstration site. Several factors, if applied, can maximize the energy savings, energy cost savings, and reduce the PCM modules size and weight. Applying these factors to the design and mode of operation of the Hybrid ECU can result in efficient and compact commercialized technologies. These factors include:

1. **PCM Selection –** PCMs with higher thermal storage capacity can significantly reduce the size and weight of the PCM module. For this application and temperature range, salt

hydrate PCMs and organic PCMs both have advantages and disadvantages. The former has higher heat storage, but can be corrosive, and the latter has lower heat storage, but better compatibility with metals. As PCM technology improves, there are candidates in both categories that offer improved performance beyond the PCM used in this study.

For this application, it is useful to compare PCMs based on energy density (MJ/m^3), a metric that accounts for both the latent heat (kJ/kg) and PCM density (kg/m^3). The organic PCM used in this study has an energy density of approximately 169 MJ/m^3. Higher energy density organic PCMs have been developed, such as Rubitherm's RT18HC, which has approximately 193 MJ/m^3, potentially reducing the PCM heat exchanger size and weight by 14%.

Salt hydrate PCMs, such as PlusIce S15 have energy densities up to 250 MJ/m^3, allowing for almost a *40% reduction* in heat exchanger size and weight. While salt hydrates are generally less compatible with metals than organic PCMs, methods exist to minimize corrosion. Heat exchangers can be manufactured using more corrosion resistant alloys. For example, AL 3005LL is a "long life" aluminum alloy with improved corrosion resistance. In addition, protective coatings can be used such as Heresite P413, a coating used by heat exchanger manufacturers to protect ECU equipment from salt corrosion.

Using a PCM with higher thermal storage capacity, with latent heat higher than 207kJ/kg, the one used in this study. Several candidates have recently been identified. Hexadecane, has a density of 0.773 kg/L at 20°C and latent heat of 236 kJ/kg. Hydrophilic Organic PCM has a density of 0.896 kg/L at 15°C and latent heat of 320 kJ/kg. The impact of using Hydrophilic Organic PCM in place of the PT18 or the Q18 PCMs, the size and weight of the PCM module can be reduced by 45%.

2. **PCM Module Design –** Using a bar-and-plate heat exchangers design will reduce the PCM module volume by 20% if a six inches wide and half inch thick is used instead of the half inch tube. With fins on the inside of the tube and in between tubes. This approach will make the PCM module smaller in size, lighter in weight, with high heat transfer coefficient.
3. **Mode of Operation –** Applying a different mode of operation to take advantage of PCM high thermal storage capacity. In this approach the PCM modules are the main system component, where the ECU supplements the PCM modules and the thermostat would trigger the air handler fan only, allowing the PCM coils to absorb heat from the room. Once the PCM is fully melted as indicated by PCM temperature, the condenser unit is activated until the PCM is fully regenerated. In this mode of operation, PCM temperature is always close to the phase change temperature, and the high latent heat capacity of PCM is better used.

In applications where peak load period electric cost is different from the rest of the day and the facilities are used 24/7, both Hybrid ECU technologies can be combined into one system to take advantage of the PLS cost savings and rest of the day energy savings. This approach will maximize the benefits of HECU technology.

7 COST ASSESSMENT

7.1 COST MODEL

The field demonstration performance data was used in estimating the life cycle operation costs of the full scale commercial PCM ECU. Using the "NIST Handbook 135" approach, given in Appendix C of NIST Handbook 135 pages 155-170, for Life Cycle Cost Analysis and data from the demonstration, the Discounted Simple Payback Period and Savings-to-Investment ratio for the commercial heat exchanger will be estimated for a 10 and 20 year period. The technology lifetime is the same as for ECU system. The technology demonstration cost models for the two configurations, which are based on current designs and did not take into account the improvements that can be achieved on both designs to reduce cost and improve functionally, are discussed below.

7.1.1 Ceiling Coils

The assembly and installation of the ceiling coils was discussed in Section 6. As with any research and development project, the lessons learned during prototype development resulted in significant design and performance differences between prototype and market-ready designs. Table 13 is separated into two sections; the upper section presents "as-built" costs for the prototype coils used during the demonstration, while the lower section details anticipated costs for mass-produced modules. The primary differences between the ceiling coils used during the demonstration, and those proposed for mass-production is the cost of the coils themselves, and the cost of the PCM.

For consistency and ease of tracking, the paragraph headings of Hardware Capitol Costs Installation Costs and Operating Costs align with Table 13

1. **Hardware Capital Costs** totalling $8,584 for the coils as demonstrated at Tyndall AFB is comprised of 11 heat exchanger coils @ $692.68 per coil, $720 of labor costs to assemble all components, and $245 for 70 pounds of Quartek Q18 PCM @ $3.50 per pound.

   Hardware capital costs for mass-produced modules were estimated at $2,730 as discussed later in the cost comparison section.

2. **Installation Costs** of $3,973 are comprised of $1,093 for tubing, eye bolts, and wire cable used to mount the ceiling coils and $2,880 for labor to install. Two people worked 16 hours on the prototype installation. The prototype installation labor estimate is based on 32 man-hours at a fully burdened rate of $90 per hour.

   Installation costs for production modules were estimated based on the experience gained during the prototype installation. The expectation is that the installation procedure could be completed by two experienced installers in 8 hours. Assuming a fully burdened rate of $90 per hour yields a total cost of $1,440.

3. **Operating Costs** as discussed in section 6.2.2 (Table 11) the retrofit was shown to produce a 19.74% energy reduction over the baseline. However, since this savings only applies to the estimated 165 days per-year when the weather conditions at this location are hot enough for PCM augmentation of the ECU to have cost-saving benefits—the resulting Facility Operating Costs for both the demonstrated prototype and mass-produced coils were reduced by only $79. Since the ceiling coils operate passively downstream of the air handler, they do not take advantage of variable energy pricing based on time-of-use.

Maintenance: This technology has no moving parts. No maintenance or repair parts or labor were required during the demonstration. There were no PCM leaks detected and no degradation of the PCM heat exchangers was observed.

In a production PCM module, the ceiling coils would be located downstream of the main ECU system's return air filter and air handler, which should help them to remain very clean. However, future anticipated maintenance would consist of cleaning the heat exchanger coils at 5-year intervals. A ROM estimate of $225 for a 2-hour service call by an ECU technician was used, for an annualized cost of $45. In practice, routine cleaning of a production PCM module would likely occur in conjunction with routine servicing/maintenance of the accompanying ECU equipment.

Hardware Lifetime: Data gathered from the PCM manufacturers, indicates that PCM in a closed system has a virtually unlimited theoretical life-span. One manufacturer had test data from 10,000 thermal cycles over a two-year test—the equivalent of 27.4 years of daily regeneration/melting cycles with no change in thermal performance. This indicates that the useful service life of the material, while unknown, should at least meet or exceed the 30-year projected service life used throughout this report.

Operator Training: This technology requires no interaction with building occupants, so no operator training is anticipated.

Residual Value: No residual value was estimated for the prototype ceiling coil heat exchangers used in the demonstration. However, mass-produced PCM ceiling coil heat exchangers will be constructed almost entirely of aluminum, with an estimated total weight of 30 pounds per ceiling coil. At current aluminum scrap prices this would yield a residual salvage value of $27 per coil. The metals recycling market is extremely volatile, making it difficult to predict the scrap value 30 years in the future.

Table 13: Ceiling Coil Cost Model

Ceiling Coils		
Cost Element	**Data Tracked During the Demonstration**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger Units	Prototype cost 11 @ $692.68 per	$ 7,619
1b. Hardware to Build	No additional hardware to build	$ -
1c. Labor to Build	Assembly of prototypes (filling with PCM)	$ 720
1d. Phase Change Material	Quartek Q18: 6.37 lbs per coil X 11 Coils @ $3.50	$ 245
2. Installation Costs		
2a. Hardware to Install	Tubing, eye bolts, wire cable, etc.	$ 1,093
2b. Labor to Install	Labor required to install (2 people, 2 Days)	$ 2,880
3. Operating Costs		
3a. Facility Operational Costs	Annual estimated reduction in energy required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (79)
3b. Maintenance	Frequency of required maintenance	None During Demo
	Labor and material per maintenance action	$ -
3c. Hardware Lifetime	Virtually indefinite. There are no moving parts and no degradation of PCM	30 Years
3d. Operator Training	None required. Function is transparent to building occupants	$ -
3e. Residual Value	No residual value was estimated for the proptotypes	$ -
Cost Element	**Projected Costs for Mass-Produced Units**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger Units	Mass-produced units 11 @ $245 per	$ 2,695
1b. Hardware to Build	(included in cost of mass-produced units)	$ -
1c. Labor to Build	(included in cost of mass-produced units)	$ -
1d. Phase Change Material	PCM 11, PCM-Expert.com 6.37 lbs per coil X 11	$ 35
2. Installation Costs		
2a. Hardware to Install	(included in cost of mass-produced units)	$ -
2b. Labor to Install	Labor required to install (2 people, 1 Day)	$ 1,440
3. Operating Costs		
3a. Facility Operational Costs	Annual energy cost reduction required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (79)
3b. Maintenance	Frequency of required maintenance	5-Year (Cleaning)
	Labor and material per maintenance action	$ 225
3c. Hardware Lifetime	Virtually indefinite. There are no moving parts and no degradation of PCM	30 Years
3d. Operator Training	None required. Function is transparent to building occupants	$ -
3e. Residual Value	Estimated scrap value of aluminum @ ~$0.90 per pound (11 coils at 30 lbs per)	$ 297

7.1.2 Peak Load Shaving

The PLS unit installed for the demonstration only had enough capacity to cool the building for two hours of the six-hour peak load period (12:00PM – 6:00PM). The cost model in Table 14 is divided into two sections; the upper section addresses cost incurred during the technology demonstration, and the lower half of the table addresses estimated costs for a mass-produced PLS system appropriately sized to cool the building for the entire six-hour peak load period. The primary differences between the peak load shaving unit used during the demonstration, and a future mass-produced unit are selection of a lower cost PCM with higher heat storage capacity, and the integration of control systems. These differences and how they would impact operational implementation of mass-produced units are discussed in greater detail in the cost comparison section and in Appendix B.

For consistency and ease of tracking, the paragraph headings of Hardware Capitol Costs Installation Costs and Operating Costs align with Table 14.

1. **Capital Hardware Costs:** The $20,793 hardware capital costs for the prototype demonstrated includes the cost of the heat exchanger ($9,000), hardware ($670), labor ($10,080), and 298 pounds of Quartek Q18 PCM @ $3.50 per pound ($1,043).

   Capitol hardware costs for a mass-produced module appropriately sized to cool the building for the entire six-hour peak load were estimated at **$**2,800. This is discussed in detail later in the cost comparison section.

2. **Installation Costs** of $3,706 for the demonstrated prototype are comprised of hardware costs of $1,203 for duct board, dampers, and actuators and labor costs of $2,520. Two people worked 14 hours on the prototype installation. Installation cost for the prototype demonstrator was estimated at 28 man-hours at a fully burdened rate of $90 per hour for a total of $2,520.

   The anticipated installation costs for a production module are more in line with installation of a 5-Ton air handler by professional ECU installers—two people for 8 hours at a fully burdened rate of $90 per hour for a total of $1,440. Some system components (extra dampers and ducting) used in the demonstration were installed for testing purposes only, and those costs were not included in the commercial installation cost estimate.

3. **Operating Costs:** As previously stated, the prototype PCM coil only had sufficient storage capacity to cool the demonstration building for two hours of the six-hour peak load period. During the demonstration, a 1-hour PCM "charging" cycle from 05:00 – 06:00 resulted in decreased ECU energy usage from 1:00 – 3:00PM during the PCM "discharging" cycle. Analysis of data collected during the PLS technology demonstration showed that 2 hours of PLS cooling yielded a tangible 1.47% reduction in ECU energy consumption and a 6.20% cost reduction compared to the baseline. However, since this savings only applies to the estimated 165 days per-year when the weather conditions at this location are hot enough for PCM augmentation of the ECU to have cost-saving benefits—the resulting Facility Operating Costs for the demonstrated prototype was reduced by only $24.

   The estimated Facility Operating Costs for an appropriately sized mass-production PLS module sized to carry the entire six-hour peak-load period is a 4.78% reduction in ECU energy consumption and 17.83% reduction in ECU energy cost, which translates to 1.29 kWh and $0.43 per day. Multiplying these values by the estimated 165 days per year when

the PLS cost/benefit ratio is expected to be above the beneficial "balance point" yields an estimated annual energy savings of 212.57 kWh for a cost avoidance of $ 70.95. Detailed analysis of the data, which led to this conclusion, is contained in Appendix B.

Maintenance: No maintenance was required during the demonstration. In a production PCM module, the anticipated maintenance would consist of cleaning the leading edge of the heat exchanger and cleaning of the condensate drain pan at 5-year intervals. A ROM estimate of $225 for a 2-hour service call by an ECU technician is the basis for an annualized cost of $45. In practice, routine cleaning of a production PCM module would likely occur in conjunction with routine servicing/maintenance of the accompanying ECU equipment.

Hardware Lifetime: During the demonstration period, no degradation of the PCM heat exchanger was observed. The test team observed the PCM for over 1,000 thermal cycles with no detectable loss in performance or functionality.

The only anticipated moving parts on a production PLS unit are flow control dampers, and possibly a separate blower fan—if one is needed to facilitate bypass and closed loop configurations in a close-quarters installation. The technology of these devices is well established and it is reasonable to anticipate a 30-year life span in a well-maintained system. As previously stated under paragraph 7.1.1, the useful service life of the PCM material, while unknown, should at least meet or exceed the 30-year projected service life used throughout this report.

Operator Training: This technology requires no interaction with building occupants, so no operator training is anticipated.

Residual Value: No residual value was estimated for the prototype PCM heat exchanger used in the demonstration. However, a mass-produced PCM heat exchanger will be constructed almost entirely of aluminum, with an estimated total weight of 1,000—1,200 pounds for the 5-ton capacity production module. At current aluminum scrap prices, this would yield a residual salvage value of $900—$1,100. The metals recycling market is extremely volatile, making it difficult to predict the scrap value 30 years in the future.

Table 14: PLS Unit Cost Model

Large Peak-Load Shaving Unit			
Cost Element	**Data Tracked During the Demonstration**	**Estimated Costs**	
1. Hardware Capital Costs			
1a. Heat Exchanger	Prototype cost	$	9,000
1b. Hardware to Build	Screws, duct board, controller, tape, etc.	$	670
1c. Labor to Build	Assembly of prototype	$	10,080
1d. Phase Change Materials	Quartek Q18: 298 lbs @ $3.50 per	$	1,043
2. Installation Costs			
2a. Hardware to Install	Duct board, dampers, actuators, tape	$	1,203
2b. Labor to Install	Labor required to install	$	2,520
3. Operating Costs			
3a. Facility Operational Costs	Annual estimated reduction in energy required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$	(24)
3b. Maintenance	Frequency of required maintenance	None During Demo	
	Labor and material per maintenance action	$	-
3c. Hardware Lifetime	Virtually indefinite, except for damper actuators	30 Years	
3d. Operator Training	None required. Function is transparent to building occupants	$	-
3e. Residual Value	No residual value was estimated for the proptotype	$	-
Cost Element	**Projected Costs for Mass-Produced Units**	**Estimated Costs**	
1. Hardware Capital Costs			
1a. Heat Exchanger	Mass-produced unit (complete assembly)	$	2,352
1b. Hardware to Build	(included in cost of mass-produced unit)	$	-
1c. Labor to Build	(included in cost of mass-produced unit)	$	-
1d. Phase Change Material	PCM 11, PCM-Expert.com 896 lbs @ $0.50 per	$	448
2. Installation Costs			
2a. Hardware to Install	(included in cost of mass-produced unit)	$	-
2b. Labor to Install	Labor required to install (2 people, 1 Day)	$	1,440
3. Operating Costs			
3a. Facility Operational Costs	Annual energy cost reduction required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$	(71)
3b. Maintenance	Frequency of required maintenance	5-Year (Cleaning)	
	Labor and material per maintenance action	$	225
3c. Hardware Lifetime	Virtually indefinite, except for damper actuators	30 Years	
3d. Operator Training	None required-function is transparent to building occupants	$	-
3e. Residual Value	Estimated scrap value of 1,000 -1,200 lbs of aluminum @ ~$0.90 per pound	$	1,000

7.2 COST DRIVERS

7.2.1 PCM-filled ceiling coils

Low operating cost is another important cost driver for the PCM technology. The installed ceiling coils operate passively with the ECU, do not increase fan energy consumption, require no modifications to the existing air handler, and there are no additional maintenance requirements for the units. A single field technician with ECU training only requires minimal additional training to check and handle the operation of the PCM-filled coils.

7.2.2 Peak Load Shaving

The major cost driver for the implementation of the HECU technology will be the reduction of the peak energy consumption and hence reduce the cost of energy consumed. Energy demand is not uniformly distributed and buildings' need for electricity is concentrated in certain places at certain times. In the United States, the annual peak demand for electricity occurs on hot summer afternoons when air conditioning is needed to maintain comfort zone conditions. Generating the electricity to meet such spikes in demand is disproportionately costly. So-called "Peaker Plants" that are too expensive and inefficient to run most of the year (usually older, dirtier power plants) are turned on for the few hours they are needed, and the resulting electricity is more expensive for customers, particularly in congested grid networks with minimal spare capacity. By transferring peak load to off-peak hours, a building manager can avoid peak hour surcharges and reduce building energy cost without impacting building operation.

An example of energy cost savings for the demonstration building located at Tyndall AFB from shifting HVAC loads to off-peak hours is shown in Table 15. A Real Time Pricing system provided by Gulf Power Company is applied to the 26 June 2016 PLS demonstration day energy usage data to provide a one-day snapshot of PLS energy cost savings. The values in the "HVAC Energy Usage (kWh)" column of Table 15 are the sums of peak and off-peak hours from the "HVAC Total kWh" columns of Table 16 and Table 17 as indicated. Similarly, the "HVAC Energy Cost" column of Table 15 represents the sums of "Graduated Time-of-Use Cost per kWh" for peak and off-peak periods of the same tables. These data demonstrate that, although the PCM unit only managed two hours from the peak period, the PCM module can shave air conditioning energy cost by 6.20%; and if an entire 6-hour peak period is managed by the unit, the energy cost saving can be as much as 20.88%. Regions with higher fluctuations in peak energy price will benefit more from PLS. Some examples are explored in Appendix B.

Table 15: Peak Load Shaving Energy Cost Savings

	HVAC Energy Usage (kWh)	HVAC Energy Cost
Demonstration Data for 2 Hours Peak Load Shaving Using PCM (Values Extracted from Upper Half of Table 16)		
Peak Hours (12:00-18:00)	8.602	$ 1.116
Off-Peak hours	23.402	$ 1.759
Total	32.004	$ 2.88
Estimated Peak Load Shaving Using PCM for Entire Peak Period (Values Extracted from Upper Half of Table 17)		
Peak Hours (12:00-18:00)	2.105	$ 0.274
Off-Peak hours	28.646	$ 2.151
Total	30.751	$ 2.43
Baseline Energy Prediction (Values Extracted from Lower Half of Table 17)		
Peak Hours (12:00-18:00)	11.094	$ 1.451
Off-Peak hours	21.386	$ 1.614
Total	32.481	$ 3.06
Cost Savings		
Actual Energy Cost Saving for 2-Hour Peak Shaving		6.20%
Estimated Energy Cost Saving for Entire Peak Shaving		20.88%

7.3 COST ANALYSIS AND COMPARISON

Simple analyses of the Ceiling Coils and Peak Load Shaving systems were conducted on the Tyndall AFB gymnasium project using the Building Life Cycle Cost (BLCC) program. In both analyses, the Base Case is identical and assumed no modifications were made to the existing ECU system.

The Base Case energy usage was derived from the Baseline model presented in the lower half of Table 21 (located in Appendix B). The total daily ECU Total kWh power of 26.93 was multiplied by 165 days, for a Base Case total of 4,442.96 kWh per year. This is the number of ECU cooling days at Tyndall AFB estimated to have ambient temperature and humidity conditions above the "tipping point" for achieving beneficial energy and/or cost savings from PCM augmentation of the ECU system. ECU energy consumption for the remaining 200 days of the year was ignored, since the PCM systems will not affect energy consumption on those days.

The lower half of Table 21 was also used to calculate the Base Case cost of energy per kWh by dividing the $ 2.41 24-Hour ECU energy cost by 26.93 kWh for an average cost of $ 0.0896 per kWh.

Future costs to maintain, repair, and replace the existing ECU system were not factored into the Base Case program, since these future costs will be incurred regardless of whether the system is augmented with PCM modules or not.

7.3.1 Ceiling Coils

The BLCC analysis of the ceiling coils is presented in Figure 49 and Figure 50. For this analysis, the 19.74% reduction in energy usage from the nonlinear energy percentage savings presented in Table 11 (under paragraph 6.2.2) was used to calculate energy usage for the Ceiling Coil alternative: 4,442.96 kWh per year (base case) x 80.26% = 3,565.93 kWh per year. This is only accounting for energy usage for the 165 days of beneficial energy savings from PCM augmentation.

The ceiling coils are located downstream of the air handler and charging or discharging of the PCM happens throughout the day, without the ability to take advantage of variable time-of-use energy prices. For this reason, the average cost of $ 0.0896 per kWh used in the BLCC base case was applied to the ceiling coil alternative.

A reliable method of developing a ROM estimate of manufacturing costs is to examine similar products not necessarily similar in function, but similar in the way they are produced. In this case, the ceiling coils in a passive PCM system are similar in both function and manufacturing processes to the heat exchanger pictured in Figure 48; and in fact, the ceiling coils used in the demonstration are virtually identical to the one pictured. For this reason, the capital costs for ceiling coils in a production environment were estimated at $245 per coil plus the cost of Kaplan Energy's PCM 11 @ $0.50 per pound needed to fill them.

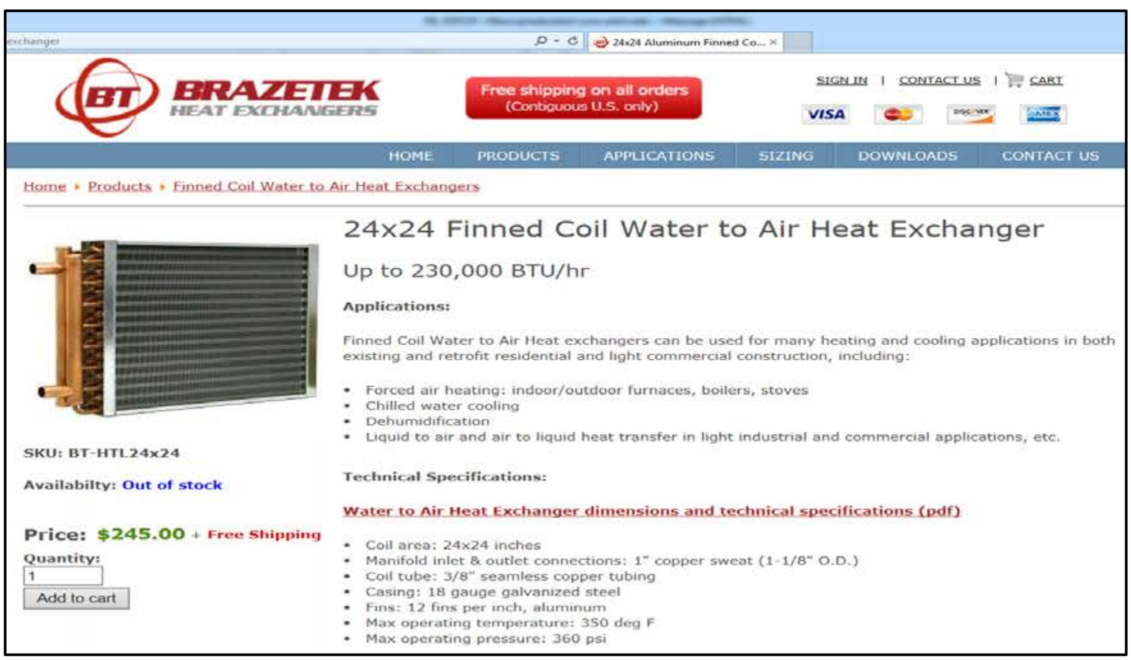


Figure 48: Mass Produced Ceiling Coil

The ceiling coils location downstream of the air handler and return air filter kept them very clean during the demonstration. However, in anticipation of cleaning at 5-year intervals, at $225 per cleaning, an annual recurring maintenance cost of $45 ($225 ÷ 5) was used in the BLCC model. The $225 cost is based on a 2-hour service call by a qualified ECU technician. In practice, this

cleaning would likely occur in conjunction with scheduled maintenance on the ECU system, with nearly negligible additive cost.

The PCM-filled ceiling coils theoretically have an indefinite life-expectancy. Even after 30 years in a closed system, there is no reason to believe that the heat storage capacity of the PCM will be diminished, or that the PCM will degrade the ceiling coils. However, in the interest of rendering a conservative estimate, a 30-year life span is assumed for the ceiling coils. Replacement cost at the end of a 30-year life span is based on the original capital purchase cost I.A.W. the BLCC program instructions. Residual scrap value of 15% is based on current scrap metal pricing. No allowance was made for recovering any of the PCM costs through re-use or recycling of the PCM—although assuming the material is still viable as expected, there could be a future market for recycling of these materials.

As the savings-to-investment ratio of 0.12, (Figure 49), and -4.03% adjusted internal rate of return, (Figure 50), indicate the PCM-filled ceiling coils are not cost effective at this time in this specific configuration. However, a 19.74% reduction in ECU energy usage – even if only for 165 days of the year– provides insight into the future viability of this technology.

NIST BLCC 5.3-13: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Standard HVAC Base case

Alternative: Ceiling Coils

General Information

File Name:	C:\Users\rmcdonald\projects\PCM Ceiling Coils Tyndall AFB.xml
Date of Study:	Thu Jun 25 12:18:39 CDT 2015
Project Name:	PCM Ceiling Coils Tyndall AFB
Project Location:	Florida
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	R.G. McDonald
Base Date:	April 1, 2014
Service Date:	October 1, 2014
Study Period:	30 years 6 months(April 1, 2014 through September 30, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$3,664	-$3,664
Future Costs:			
Energy Consumption Costs	$8,271	$6,639	$1,633
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$869	-$869
Capital Replacements	$0	$3,719	-$3,719
Residual Value at End of Study Period	$0	-$784	$784
Subtotal (for Future Cost Items)	$8,271	$10,442	-$2,171
Total PV Life-Cycle Cost	$8,271	$14,107	-$5,835

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$764
- Increased Total Investment	$6,599
Net Savings	-$5,835

Savings-to-Investment Ratio (SIR)

SIR = 0.12

Figure 49: BLCC Analysis of Ceiling Coils (Page 1)

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = -4.03%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year	0
Simple Payback is negated in year	1
Discounted Payback occurs in year	0
Discounted Payback is negated in year	1

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	4,443.0 kWh	3,565.9 kWh	877.0 kWh	26,309.7 kWh

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	15.2 MBtu	12.2 MBtu	3.0 MBtu	89.8 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	2,902.14 kg	2,329.26 kg	572.88 kg	17,185.48 kg
SO2	8.38 kg	6.73 kg	1.65 kg	49.63 kg
NOx	4.56 kg	3.66 kg	0.90 kg	26.99 kg
Total:				
CO2	2,902.14 kg	2,329.26 kg	572.88 kg	17,185.48 kg
SO2	8.38 kg	6.73 kg	1.65 kg	49.63 kg
NOx	4.56 kg	3.66 kg	0.90 kg	26.99 kg

Figure 50: BLCC Analysis of Ceiling Coils (Page 2)

7.3.2 Peak Load Shaving System

The BLCC analysis of the Peak Load Shaving System is presented in Figure 52 and Figure 53. The upper half of Table 21 (Located in Appendix B) was also used to calculate the energy usage by multiplying 25.64 by 165 days of beneficial PCM augmentation for a total of 4,230.39 kWh.

The PLS unit is located downstream of the air handler, but damper and ducting configurations enabled charging of the PCM in a closed-loop configuration during off-peak hours when energy costs—and demand for ECU cooling were both at their lowest—taking advantage of variable time-of-use energy prices. The cost of energy per kWh was calculated by dividing the $ 1.98 24-Hour ECU energy cost by 25.64 kWh for an average cost of $ 0.0773 per kWh.

The cost of building and installing the prototype PLS system, including installation was $23,979.60. With annual energy cost savings of under $100 per year, the cost of the prototype system precludes any reasonable return-on-investment period, even with a projected 30-year life span. However, the retail cost of a mass-produced unit would be approximately 16% of the prototype cost. A reliable method of developing a ROM estimate of manufacturing costs is to examine similar products—not necessarily similar in function, but similar in the way they are produced. In this case, a 5-ton capacity PLS unit is very similar in both function and manufacturing processes to an ECU air handling unit. Both consist of four primary components: a heat-exchanger, enclosure/cabinet, system controls, and blower fan. The primary difference between an air handler and a mass-produced PLS unit is the phase change material contained within the heat exchanger coil, and the size of the unit—a PCM-filled PLS unit is larger and heavier than a conventional air handler. It can be reasonably argued and assumed that a 5-ton capacity PLS unit would cost more to manufacture than a similarly-sized air handler due to the larger size and greater amounts of metal used in manufacturing.

For this reason, a 10-ton air handler, Figure 51, which retails for about $2,352 was selected as a more realistic cost comparison model. The addition of 896 pounds of PCM 11, at $0.50 per pound, and installation costs of $1,440 brings the estimated cost of a manufactured PCM module to $4,240.

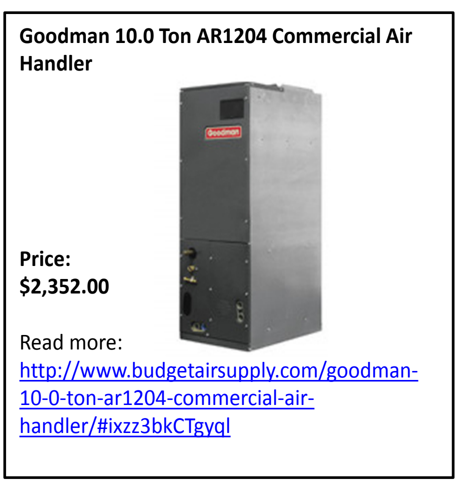


Figure 51: Typical 10-Ton Air Handler

The PLS unit's location downstream of the air handler and return air filter kept it very clean during the demonstration. However, in anticipation of cleaning at 5-year intervals, at $225 per cleaning, an annual recurring maintenance cost of $45 ($225 ÷ 5) was used in the BLCC model. The $225

cost is based on a 2-hour service call by a qualified ECU technician. In practice, this cleaning would likely occur in conjunction with scheduled maintenance on the ECU system, with nearly negligible additive cost.

As discussed with the ceiling coils, a PCM-filled heat exchanger unit has an indefinite theoretical life-expectancy. However, in the interest of rendering a conservative estimate, a 30-year life span is assumed for the PLS unit, the same as for the ceiling coils. Replacement cost at the end of a 30-year life span is based on the original capital purchase cost I.A.W. the BLCC program instructions. As with the ceiling coils, the residual scrap value of 15% is based on current scrap metal pricing, and no provisions were included for salvaging the PCM, which may or may not have residual value in 30 years.

A simple analysis in the Building Life Cycle Cost (BLCC) program, Figure 52 and Figure 53, based on a 30-year life cycle, confirmed that the PLS alternative is not cost effective at this time due to a Savings-to-Investment Ratio (SIR) of 0.2 and Adjusted Internal Rate of Return (AIRR) of -2.36%.

NIST BLCC 5.3-13: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Standard HVAC Base case

Alternative: Peak Load Shaving Unit

General Information

File Name:	C:\Users\rmcdonald\projects\PCM Peak Load Shaving Tyndall AFB.xml
Date of Study:	Wed Jun 24 10:07:00 CDT 2015
Project Name:	PCM Peak Load Shaving Tyndall AFB
Project Location:	Florida
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	R.G. McDonald
Base Date:	April 1, 2014
Service Date:	October 1, 2014
Study Period:	30 years 6 months(April 1, 2014 through September 30, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$4,178	-$4,178
Future Costs:			
Energy Consumption Costs	$8,271	$6,797	$1,475
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$4,240	-$4,240
Residual Value at End of Study Period	$0	-$894	$894
Subtotal (for Future Cost Items)	$8,271	$10,143	-$1,871
Total PV Life-Cycle Cost	$8,271	$14,321	-$6,049

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$1,475
- Increased Total Investment	$7,524
Net Savings	-$6,049

Savings-to-Investment Ratio (SIR)

SIR = 0.20

Figure 52: BLCC Analysis of Peak Load Shaving Unit (Page 1)

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = -2.36%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year	0
Simple Payback is negated in year	1
Discounted Payback occurs in year	0
Discounted Payback is negated in year	1

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	4,443.0 kWh	4,230.4 kWh	212.6 kWh	6,377.1 kWh

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	15.2 MBtu	14.4 MBtu	0.7 MBtu	21.8 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	2,902.15 kg	2,763.29 kg	138.86 kg	4,165.52 kg
SO2	8.38 kg	7.98 kg	0.40 kg	12.03 kg
NOx	4.56 kg	4.34 kg	0.22 kg	6.54 kg
Total:				
CO2	2,902.15 kg	2,763.29 kg	138.86 kg	4,165.52 kg
SO2	8.38 kg	7.98 kg	0.40 kg	12.03 kg
NOx	4.56 kg	4.34 kg	0.22 kg	6.54 kg

Figure 53: BLCC Analysis of Peak Load Shaving Unit (Page 2)

However, reductions of 4.78% in ECU energy consumption and 17.83% in the cost of energy used (Table 21in Appendix B) for ECU cooling at the Tyndall AFB demonstration site are encouraging statistics. ARA engineers believe the “tipping point” to making PLS technology more cost-effective are achievable through further design enhancements. Improved heat transfer efficiency; intelligent control systems to optimize time and duration of charging and discharging cycles; and scaling the technology to larger systems where these percentage reductions in ECU energy consumption and costs will have a greater impact and shorter payback periods.

As advances in PCM technology and manufacturing methods are made, the peak load shaving PCM unit will become smaller, lighter and less expensive. Discussion of future performance enhancements through selection of PCM with higher energy density than the Quartek Q18 are included in Appendix B. The viability of the technology in other locales with large fluctuations in hourly electricity rates and ambient temperature is also touched on in Appendix B.

8 IMPLEMENTATION ISSUES

8.1 CEILING COILS

There are fewer options for ceiling coil installation, as installation location is dictated by the ceiling register locations in the facility. Building codes and ASHRAE standards should still be followed, but an additional safety concern with this technology is ensuring that the coils are properly supported, since they are overhead. PCM-filled ceiling coils that cover a 2’x2’ register, such as the ones used in the demonstration, weigh approximately 40 lbs and are too heavy to be supported by a drop ceiling. Therefore, the support system should be installed in the attic space using ceiling joists. During installation, the support system should be inspected to make sure it is safe during severe weather such as earthquakes to avoid injury caused by the overhead coils.

8.2 PEAK LOAD SHAVING

The peak load shaving coil can be installed using a process similar to installing an air handler. Installing the PLS coil into new buildings is quite straight forward, as the building can be designed to allow sufficient space for the PCM module to sit next to the air handler in the mechanical room. For retrofits, however, the installation must be determined based on the specific facility. If there is not sufficient space in the mechanical room, the PCM module can be located in the attic space, outside on a concrete slab, on a rooftop, or on the floor in an unused room of the facility. Of these options, the attic space is the most convenient, since the duct is typically already in the attic space, which reduces the length of duct required for the PCM module and minimizes pressure drop. In other locations, such as outside or on the roof, holes must be cut through walls to allow the duct to run to the PCM module and back inside.

Building codes and ASHRAE standards will serve as the main guidelines during the install and should be followed to ensure that the unit is properly supported and maintains fire codes and airflow requirements. For the demonstration building, the ideally sized coil contained 980 lbs of PCM in addition to the weight of the heat exchanger, bringing the total weight of the PCM module to approximately 1 ton. The footprint would be approximately 10 square feet, so the load per square foot is 220 lbs. Depending on the install location, the unit might require additional support. If the unit cannot be adequately supported using the existing structure, a stand can be constructed to support the unit.

The end-user wanted to make sure the unit was well supported and that installation did not interfere with any fire codes pertaining to building access. During the demonstration, ARA installed the unit on the floor in the exercise room, while adhering to fire codes. The unit was installed without blocking any doors or impeding exit in case of an emergency. The only other end-user concern was floor space. This is a valid concern, which is why the ideal location for the unit was determined to be in the attic space.

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APPENDICES

APPENDIX A: Points of Contacts

POC Name	ORGANIZATION Name and Address	Phone, Fax, and E-mail	Role in Project
Reza Salavani	Tyndall Air Force Base Air Force Civil Engineer Center (AFCEC) 119 Alabama Ave, Tyndall Air Force Base, FL 32403	Phone: (850) 283-3715 Fax: (850) 283-6064 Reza.Salavani@us.af.mil	Permissions for facility use
Gilbert Walker	Tyndall Air Force Base Civil Engineering Squadron (CES) 119 Alabama Ave, Tyndall Air Force Base, FL 32403	Phone: (850) 283-2404 Gilbert.walker@us.af.mil	Civil Engineering Squadron, Energy Manager, (Jonathan Caldwell was in this position during the retrofit)
Marvin Couch	Tyndall Air Force Base Civil Engineering Squadron (CES) 119 Alabama Ave, Tyndall Air Force Base, FL 32403	Phone: (850) 283-2753 Marvin.couch.ctr@us.af.mil	Civil Engineering Squadron, Supervisor, Foreman of the Area (Kevin Moxley was in this position during the retrofit)
Trey St. Amant	Tyndall Air Force Base Civil Engineering Squadron (CES) 119 Alabama Ave, Tyndall Air Force Base, FL 32403	Phone: (850) 283-3288 Leo.st_amant.1.ctr@us.af.mil	Civil Engineering Squadron, Facilities Maintenance Supervisor (Kevin Moxley was in this position during the retrofit)
Michael Mifsud	Tyndall Air Force Base Air Force Civil Engineer Center (AFCEC) 119 Alabama Ave, Tyndall Air Force Base, FL 32403	Phone: (850) 283-2989 Fax: (850) 283-9710 Michael.mifsud@us.af.mil	Chief, Logistics Support
Dr. Reyad Sawafta	QuarTek Corporation 120 E Pritchard Street, Asheboro, NC 27203	Phone: (336) 316-0065 Fax: (336) 316-0118 rsawafta@quartekcorp.com	Manufacturer, Q18 PCM
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Jake Goldberg	Diversified Heat Transfer 439 Main Road, Towaco, NJ 07082	Phone: (800) 221-1522 Fax: (718) 386-7809 jgoldberg@dhtnet.com	Manufacturer, Demonstration Heat Exchangers
Josiah Wintermute	Petro-Lubricant Testing Laboratories 116 Sunset Inn Road PO Box 300, Lafayette, N.J. 07848	Phone: (973) 579-3448 Fax: (973) 579-9447 Tech@petrolube.com	PCM Testing, Autoignition, Flash Point, , Density, Surface Tension, Viscosity, Evaporation Rate
George Page	FAI Laboratories 825 Chance Road, Marietta, GA 30066	Phone: (770) 928-1930 George@FAI.us	PCM Testing, Differential Scanning Calorimetry (DSC)
Chris Fowler	Nelson & Company 1622 Hickman Road, Jacksonville, FL 32216	Phone: (904) 807-9899 Fax: (904) 483-3005 cfowler@ncjax.com	Manufacturer, Duct Mount Station to Measure Air Flow
Jerry Tolbert	Bush Air Conditioning 1750 Frankford Ave, Panama City, FL 32405	Phone: (850) 769-0327	ECU Contractor, Installed Pre-Demonstration Air Conditioning System
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APPENDIX B: Extrapolation of PLS Prototype Data Analysis to Mass-Production PLS Unit

Analysis of the data collected throughout the PLS demonstration confirmed that the PLS alternative—as built for the demonstration—is not economically feasible at this time. However, the 4.78% reduction in ECU energy consumption and 17.83% reduction in the cost of energy (Table 21)used for ECU cooling at the Tyndall AFB demonstration site are encouraging. Data collected and analysed throughout this project has convinced ARA engineers that the "tipping point" to making PLS technology more cost-effective will be achieved through further design enhancements to improve heat transfer efficiency, selection of lower cost PCM with higher energy density, and intelligent control systems to optimize time and duration of charging and discharging cycles.

This appendix discusses several ways that the cost-effectiveness of PLS technology could be improved. These are, building a unit sized to carry the entire summer-time cooling peak period, selection of PCM with a higher energy density, and applying the technology in locales with greater day/night temperature swings and/or large fluctuations in hourly energy costs.

Larger Storage Capacity PLS Unit: The first topic to explore is the demonstration data extrapolated to a unit with sufficient energy-storage capacity to provide cooling for the entire 6-hour peak load period. This was touched on very briefly in section 7, but the detailed analysis was reserved for this appendix. PCM-11 the proposed PCM for a production system was selected due to its lower density and greater thermal efficiency than other PCMs studied. This will enable the same thermal storage capacity with less weight and footprint, making it easier and less expensive to build a larger capacity PLS unit.

The prototype PCM coil used in the demonstration only had sufficient storage capacity to cool the demonstration building for two hours of the six hours peak load period. Table 16 provides a snapshot of data for 26 June 2014. The upper half of Table 16 shows actual hourly averaged data from the demonstration day. Note the increased ECU energy usage from 05:00 – 06:00 during the 1-hour regeneration cycle and decrease in ECU energy usage from 1:00 – 3:00PM during the PCM melting cycle. The lower half of Table 16 established a "baseline" comparison by fitting a curve to the hourly ECU energy consumption during hours where the PCM coil was not used. This curve was only used to predict the energy that would have been used by the ECU system during charging and discharging periods if PLS was not used, and these changes are indicated in the lower half of Table 16 as "predicted". This approach gave the baseline energy consumption of the building with the ceiling coils in place to separate the impact of the PLS coil on building energy savings and cost from the presence of the ceiling coils. These data demonstrated that 2 hours of PLS yielded a tangible 1.47% reduction in ECU energy consumption and a 6.20% cost reduction compared to the baseline.

Table 16: PLS Demonstration Data; 26 June 2014

		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non HVAC kWh	AirHand kWh	Compressor kWh	HVAC Total kWh	Total HVAC Energy Cost	Local Time-of-Use Cost per kWh	
Actual 26 June 2014	Off-Peak	0:00-01:00	1.744960185	$ 0.125410289	0.721260435	0.184504381	0.839195369	1.023699750	$ 0.073573301	$ 0.07187	
		01:00-02:00	1.789462856	$ 0.128125540	0.774010370	0.180498842	0.834953644	1.015452486	$ 0.072706398	$ 0.07160	
		02:00-03:00	1.908114887	$ 0.135895942	0.818386085	0.184225865	0.905502937	1.089728802	$ 0.077610485	$ 0.07122	
		03:00-04:00	1.812143765	$ 0.128789057	0.717850314	0.192156357	0.902137095	1.094293452	$ 0.077771436	$ 0.07107	
		04:00-05:00	1.769193927	$ 0.126497366	0.711102925	0.191002771	0.867088231	1.058091002	$ 0.075653507	$ 0.07150	
		05:00-06:00	3.617870761	$ 0.259328976	0.728050854	0.342076196	2.547743711	2.889819907	$ 0.207142291	$ 0.07168	Charge
		06:00-07:00	1.649603196	$ 0.119134343	0.699962552	0.152766879	0.796873765	0.949640644	$ 0.068583047	$ 0.07222	
		07:00-08:00	1.221046492	$ 0.089234078	0.535211613	0.140549747	0.545285132	0.685834879	$ 0.050120813	$ 0.07308	
		08:00-09:00	1.280130216	$ 0.094166379	0.552440379	0.140204980	0.587484858	0.727689838	$ 0.053528864	$ 0.07356	
		09:00-10:00	2.734949145	$ 0.203890459	1.790699804	0.169715722	0.774533618	0.944249340	$ 0.070393788	$ 0.07455	
		10:00-11:00	3.297215256	$ 0.260348117	1.191680892	0.730913890	1.374620474	2.105534364	$ 0.166252993	$ 0.07896	
		11:00-12:00	4.643521899	$ 0.378121988	1.239079602	0.338404793	3.066037504	3.404442297	$ 0.277223736	$ 0.08143	
	Peak	12:00-13:00	2.353978261	$ 0.307406021	0.333874810	0.245352005	1.774751445	2.020103450	$ 0.263805310	$ 0.13059	
		13:00-14:00	0.679911225	$ 0.092080377	0.330843505	0.349067721	0.000000000	0.349067721	$ 0.047274241	$ 0.13543	Discharge
		14:00-15:00	1.742159469	$ 0.230574806	0.329521851	0.344112034	1.068525583	1.412637617	$ 0.186962589	$ 0.13235	
		15:00-16:00	1.904513536	$ 0.250710162	0.339749783	0.214960901	1.349802852	1.564763753	$ 0.205985500	$ 0.13164	Catch Up
		16:00-17:00	2.146987112	$ 0.281877938	0.324797283	0.249804420	1.572385410	1.822189829	$ 0.239235303	$ 0.13129	
		17:00-18:00	1.770161485	$ 0.213711596	0.336707433	0.204924954	1.228529097	1.433454052	$ 0.173060908	$ 0.12073	
	Off-Peak	18:00-19:00	1.738476418	$ 0.137270098	0.334750703	0.207576054	1.196149661	1.403725715	$ 0.110838182	$ 0.07896	
		19:00-20:00	1.545018168	$ 0.122319088	0.379380648	0.180021191	0.985616328	1.165637519	$ 0.092283522	$ 0.07917	
		20:00-21:00	1.454951693	$ 0.109747006	0.413301858	0.176766879	0.864882956	1.041649835	$ 0.078571647	$ 0.07543	
		21:00-22:00	1.772095675	$ 0.132145174	0.627072533	0.185384569	0.959638573	1.145023142	$ 0.085384376	$ 0.07457	
		22:00-23:00	1.196518568	$ 0.087704811	0.415619303	0.157352080	0.623547185	0.780899265	$ 0.057239916	$ 0.07330	
		23:00-24:00	1.327824282	$ 0.096798390	0.451463945	0.162052903	0.714307435	0.876360338	$ 0.063886669	$ 0.07290	
		24-Hour Total	47.100808479	$ 4.111288002	15.096819482	5.624396133	26.379592864	32.003988997	$ 2.875088823		
% kWh Reduction			0.63%		0.00%	-6.98%	2.55%	**1.47%**			
	% Cost Reduction			3.75%					**6.20%**		
		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non HVAC kWh	AirHand kWh	Compressor kWh	HVAC Total kWh	Total HVAC Energy Cost	Local Time-of-Use Cost per kWh	
Baseline 26 June 2014	Off-Peak	0:00-01:00	1.744960185	$ 0.125410289	0.721260435	0.184504381	0.839195369	1.023699750	$ 0.073573301	$ 0.07187	
		01:00-02:00	1.789462856	$ 0.128125540	0.774010370	0.180498842	0.834953644	1.015452486	$ 0.072706398	$ 0.07160	
		02:00-03:00	1.908114887	$ 0.135895942	0.818386085	0.184225865	0.905502937	1.089728802	$ 0.077610485	$ 0.07122	
		03:00-04:00	1.812143765	$ 0.128789057	0.717850314	0.192156357	0.902137095	1.094293452	$ 0.077771436	$ 0.07107	
		04:00-05:00	1.769193927	$ 0.126497366	0.711102925	0.191002771	0.867088231	1.058091002	$ 0.075653507	$ 0.07150	
		05:00-06:00	1.709398562	$ 0.122529689	0.728050854	0.171884825	0.831980998	0.874531766	$ 0.062686437	$ 0.07168	Predicted
		06:00-07:00	1.649603196	$ 0.119134343	0.699962552	0.152766879	0.796873765	0.949640644	$ 0.068583047	$ 0.07222	
		07:00-08:00	1.221046492	$ 0.089234078	0.535211613	0.140549747	0.545285132	0.685834879	$ 0.050120813	$ 0.07308	
		08:00-09:00	1.280130216	$ 0.094166379	0.552440379	0.140204980	0.587484858	0.727689838	$ 0.053528864	$ 0.07356	
		09:00-10:00	2.734949145	$ 0.203890459	1.790699804	0.169715722	0.774533618	0.944249340	$ 0.070393788	$ 0.07455	
		10:00-11:00	3.297215256	$ 0.260348117	1.191680892	0.730913890	1.374620474	2.105534364	$ 0.166252993	$ 0.07896	
		11:00-12:00	4.643521899	$ 0.378121988	1.239079602	0.338404793	3.066037504	3.404442297	$ 0.277223736	$ 0.08143	
	Peak	12:00-13:00	2.353978261	$ 0.307406021	0.333874810	0.245352005	1.774751445	2.020103450	$ 0.263805310	$ 0.13059	
		13:00-14:00	2.302230474	$ 0.311791073	0.330843505	0.246465109	1.724159936	1.901951456	$ 0.257581286	$ 0.13543	Predicted
		14:00-15:00	2.169213226	$ 0.287095371	0.329521851	0.236080070	1.600252226	1.963349387	$ 0.259849291	$ 0.13235	
		15:00-16:00	2.061529024	$ 0.271379681	0.339749783	0.228954066	1.499226585	1.953291610	$ 0.257131308	$ 0.13164	Predicted
		16:00-17:00	2.146987112	$ 0.281877938	0.324797283	0.249804420	1.572385410	1.822189829	$ 0.239235303	$ 0.13129	
		17:00-18:00	1.770161485	$ 0.213711596	0.336707433	0.204924954	1.228529097	1.433454052	$ 0.173060908	$ 0.12073	
	Off-Peak	18:00-19:00	1.738476418	$ 0.137270098	0.334750703	0.207576054	1.196149661	1.403725715	$ 0.110838182	$ 0.07896	
		19:00-20:00	1.545018168	$ 0.122319088	0.379380648	0.180021191	0.985616328	1.165637519	$ 0.092283522	$ 0.07917	
		20:00-21:00	1.454951693	$ 0.109747006	0.413301858	0.176766879	0.864882956	1.041649835	$ 0.078571647	$ 0.07543	
		21:00-22:00	1.772095675	$ 0.132145174	0.627072533	0.185384569	0.959638573	1.145023142	$ 0.085384376	$ 0.07457	
		22:00-23:00	1.196518568	$ 0.087704811	0.415619303	0.157352080	0.623547185	0.780899265	$ 0.057239916	$ 0.07330	
		23:00-24:00	1.327824282	$ 0.096798390	0.451463945	0.162052903	0.714307435	0.876360338	$ 0.063886669	$ 0.07290	
		24-Hour Total	47.40	$ 4.27	15.10	5.26	27.07	32.48	$ 3.06		

In an ideal case, the PCM module would carry the entire six-hour peak-load period and require 1.5 hours for regeneration to guarantee complete solidification and avoid overcharging. Straightforward calculations make it possible to extrapolate energy consumption (kWh) and cost of operation for a 5-ton unit with sufficient capacity to cool the facility for the entire six-hour peak-load period using these criteria.

To determine the impact of an ideally sized PLS unit on energy and cost reduction for the above day, the baseline established in the lower half of Table 16 was used as the baseline for an ideal

case in the lower half of Table 17. These baseline values were then adjusted during charging and discharging periods to form the upper half of Table 17 using the steps outlined in section 6.4.2.

Non-ECU building loads (lights, water heater, powered gym equipment, and floor fans) and pricing is unaltered and carried over directly from Table 16.

Table 17: Ideal PLS Operation for June 26, 2014

		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non ECU kWh	24-Hour Non-ECU Total Energy Cost	AirHand kWh	Compressor kWh	24-Hour Total Compressor Energy Cost	HVAC Total kWh	24-Hour ECU Energy Cost	Graduated Time-of-Use Cost per kWh	
Ideal 26 June 2014	Off-Peak	0:00-01:00	1.744960185	$ 0.125410289	0.721260435	$ 0.051836987	0.184504381	0.839195369	$ 0.060312971	1.023699750	$ 0.073573301	$ 0.07187	
		01:00-02:00	1.789462856	$ 0.128125540	0.774010370	$ 0.055419142	0.180498842	0.834953644	$ 0.059782681	1.015452486	$ 0.072706398	$ 0.07160	
		02:00-03:00	1.908114887	$ 0.135895942	0.818386085	$ 0.058285457	0.184225865	0.905502937	$ 0.064489919	1.089728802	$ 0.077610485	$ 0.07122	
		03:00-04:00	3.999830314	$ 0.284267940	0.717850314	$ 0.051017622	0.350801626	2.931178374	$ 0.208318847	3.281980000	$ 0.233250319	$ 0.07107	Charge
		04:00-05:00	3.779682925	$ 0.270247329	0.711102925	$ 0.050843859	0.350801626	2.717778374	$ 0.194321154	3.068580000	$ 0.219403470	$ 0.07150	Charge Half Hour & Catch Up
		05:00-06:00	2.220677074	$ 0.159178133	0.728050854	$ 0.052186685	0.171884825	1.320741395	$ 0.094670743	1.492626220	$ 0.106991447	$ 0.07168	Residual Catch Up
		06:00-07:00	1.649603196	$ 0.119134343	0.699962552	$ 0.050551296	0.152766879	0.796873765	$ 0.057550223	0.949640644	$ 0.068583047	$ 0.07222	
		07:00-08:00	1.221046492	$ 0.089234078	0.535211613	$ 0.039113265	0.140549747	0.545285132	$ 0.039849437	0.685834879	$ 0.050120813	$ 0.07308	
		08:00-09:00	1.280130216	$ 0.094166379	0.552440379	$ 0.040637514	0.140204980	0.587484858	$ 0.043215386	0.727689838	$ 0.053528864	$ 0.07356	
		09:00-10:00	2.734949145	$ 0.203890459	1.790699804	$ 0.133496670	0.169715722	0.774533618	$ 0.057741481	0.944249340	$ 0.070393788	$ 0.07455	
		10:00-11:00	3.297215256	$ 0.260348117	1.191680892	$ 0.094095123	0.730913890	1.374620474	$ 0.108540033	2.105534364	$ 0.166252993	$ 0.07896	
		11:00-12:00	4.643521899	$ 0.378121988	1.239079602	$ 0.100898252	0.338404793	3.066037504	$ 0.249667434	3.404442297	$ 0.277223736	$ 0.08143	
	Peak	12:00-13:00	0.684676437	$ 0.089411896	0.333874810	$ 0.043600711	0.350801626	0.000000000	$ -	0.350801626	$ 0.045811184	$ 0.13059	
		13:00-14:00	0.681645131	$ 0.092315200	0.330843505	$ 0.044806136	0.350801626	0.000000000	$ -	0.350801626	$ 0.047509064	$ 0.13543	
		14:00-15:00	0.680323478	$ 0.090040812	0.329521851	$ 0.043612217	0.350801626	0.000000000	$ -	0.350801626	$ 0.046428595	$ 0.13235	Discharge
		15:00-16:00	0.690551410	$ 0.090904188	0.339749783	$ 0.044724661	0.350801626	0.000000000	$ -	0.350801626	$ 0.046179526	$ 0.13164	
		16:00-17:00	0.675598909	$ 0.088699381	0.324797283	$ 0.042642635	0.350801626	0.000000000	$ -	0.350801626	$ 0.046056746	$ 0.13129	
		17:00-18:00	0.687509060	$ 0.083002969	0.336707433	$ 0.040650688	0.350801626	0.000000000	$ -	0.350801626	$ 0.042352280	$ 0.12073	
	Off-Peak	18:00-19:00	4.182096329	$ 0.330218326	0.334750703	$ 0.026431916	0.350801626	3.496544000	$ 0.276087114	3.847345626	$ 0.303786411	$ 0.07896	Catch Up
		19:00-20:00	1.545018168	$ 0.122319088	0.379380648	$ 0.030035566	0.180021191	0.985616328	$ 0.078031245	1.165637519	$ 0.092283522	$ 0.07917	
		20:00-21:00	1.454951693	$ 0.109747006	0.413301858	$ 0.031175359	0.176766879	0.864882956	$ 0.065238121	1.041649835	$ 0.078571647	$ 0.07543	
		21:00-22:00	1.772095675	$ 0.132145174	0.627072533	$ 0.046760799	0.185384569	0.959638573	$ 0.071560248	1.145023142	$ 0.085384376	$ 0.07457	
		22:00-23:00	1.196518568	$ 0.087704811	0.415619303	$ 0.030464895	0.157352080	0.623547185	$ 0.045706009	0.780899265	$ 0.057239916	$ 0.07330	
		23:00-24:00	1.327824282	$ 0.096798390	0.451463945	$ 0.032911722	0.162052903	0.714307435	$ 0.052073012	0.876360338	$ 0.063886669	$ 0.07290	
		24-Hour Total	45.85	$ 3.66	15.10	$ 1.24	6.41	24.34	$ 1.83	30.75	$ 2.43		
Power Reduction			3.27%		0.00%		-21.97%	10.09%		5.33%			
	% Cost Reduction			14.28%		0.00%			28.71%		20.88%		

		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non HVAC kWh	24-Hour Non-HVAC Total Energy Cost	AirHand kWh	Compressor kWh	24-Hour Total Compressor Energy Cost	HVAC Total kWh	24-Hour HVAC Energy Cost	Graduated Time-of-Use Cost per kWh	
Baseline 26 June 2014	Off-Peak	0:00-01:00	1.744960185	$ 0.125410289	0.721260435	$ 0.051836987	0.184504381	0.839195369	$ 0.060312971	1.023699750	$ 0.073573301	$ 0.07187	
		01:00-02:00	1.789462856	$ 0.128125540	0.774010370	$ 0.055419142	0.180498842	0.834953644	$ 0.059782681	1.015452486	$ 0.072706398	$ 0.07160	
		02:00-03:00	1.908114887	$ 0.135895942	0.818386085	$ 0.058285457	0.184225865	0.905502937	$ 0.064489919	1.089728802	$ 0.077610485	$ 0.07122	
		03:00-04:00	1.812143765	$ 0.128789057	0.717850314	$ 0.051017622	0.192156357	0.902137095	$ 0.064114883	1.094293452	$ 0.077771436	$ 0.07107	
		04:00-05:00	1.769193927	$ 0.126497366	0.711102925	$ 0.050843859	0.191002771	0.867088231	$ 0.061996809	1.058091002	$ 0.075653507	$ 0.07150	
		05:00-06:00	1.709398562	$ 0.122529689	0.728050854	$ 0.052186685	0.171884825	0.831980998	$ 0.059636398	0.874531766	$ 0.062686437	$ 0.07168	Predicted
		06:00-07:00	1.649603196	$ 0.119134343	0.699962552	$ 0.050551296	0.152766879	0.796873765	$ 0.057550223	0.949640644	$ 0.068583047	$ 0.07222	
		07:00-08:00	1.221046492	$ 0.089234078	0.535211613	$ 0.039113265	0.140549747	0.545285132	$ 0.039849437	0.685834879	$ 0.050120813	$ 0.07308	
		08:00-09:00	1.280130216	$ 0.094166379	0.552440379	$ 0.040637514	0.140204980	0.587484858	$ 0.043215386	0.727689838	$ 0.053528864	$ 0.07356	
		09:00-10:00	2.734949145	$ 0.203890459	1.790699804	$ 0.133496670	0.169715722	0.774533618	$ 0.057741481	0.944249340	$ 0.070393788	$ 0.07455	
		10:00-11:00	3.297215256	$ 0.260348117	1.191680892	$ 0.094095123	0.730913890	1.374620474	$ 0.108540033	2.105534364	$ 0.166252993	$ 0.07896	
		11:00-12:00	4.643521899	$ 0.378121988	1.239079602	$ 0.100898252	0.338404793	3.066037504	$ 0.249667434	3.404442297	$ 0.277223736	$ 0.08143	
	Peak	12:00-13:00	2.353978261	$ 0.307406021	0.333874810	$ 0.043600711	0.245352005	1.774751445	$ 0.231764791	2.020103450	$ 0.263805310	$ 0.13059	
		13:00-14:00	2.302230474	$ 0.311791073	0.330843505	$ 0.044806136	0.246465109	1.724159936	$ 0.233502980	1.901951456	$ 0.257581286	$ 0.13543	Predicted
		14:00-15:00	2.169213226	$ 0.287095371	0.329521851	$ 0.043612217	0.236080070	1.600252226	$ 0.211793382	1.963349387	$ 0.259849291	$ 0.13235	
		15:00-16:00	2.061529024	$ 0.271379681	0.339749783	$ 0.044724661	0.228954066	1.499226585	$ 0.197358188	1.953291610	$ 0.257131308	$ 0.13164	Predicted
		16:00-17:00	2.146987112	$ 0.281877938	0.324797283	$ 0.042642635	0.249804420	1.572385410	$ 0.206438480	1.822189829	$ 0.239235303	$ 0.13129	
		17:00-18:00	1.770161485	$ 0.213711596	0.336707433	$ 0.040650688	0.204924954	1.228529097	$ 0.148320318	1.433454052	$ 0.173060908	$ 0.12073	
	Off-Peak	18:00-19:00	1.738476418	$ 0.137270098	0.334750703	$ 0.026431916	0.207576054	1.196149661	$ 0.094447977	1.403725715	$ 0.110838182	$ 0.07896	
		19:00-20:00	1.545018168	$ 0.122319088	0.379380648	$ 0.030035566	0.180021191	0.985616328	$ 0.078031245	1.165637519	$ 0.092283522	$ 0.07917	
		20:00-21:00	1.454951693	$ 0.109747006	0.413301858	$ 0.031175359	0.176766879	0.864882956	$ 0.065238121	1.041649835	$ 0.078571647	$ 0.07543	
		21:00-22:00	1.772095675	$ 0.132145174	0.627072533	$ 0.046760799	0.185384569	0.959638573	$ 0.071560248	1.145023142	$ 0.085384376	$ 0.07457	
		22:00-23:00	1.196518568	$ 0.087704811	0.415619303	$ 0.030464895	0.157352080	0.623547185	$ 0.045706009	0.780899265	$ 0.057239916	$ 0.07330	
		23:00-24:00	1.327824282	$ 0.096798390	0.451463945	$ 0.032911722	0.162052903	0.714307435	$ 0.052073012	0.876360338	$ 0.063886669	$ 0.07290	
		24-Hour Total	47.40	$ 4.27	15.10	$ 1.24	5.26	27.07	$ 2.56	32.48	$ 3.06		

In Table 17, ideal PLS operation on June 26, 2014 yielded a **5.33%** reduction in ECU energy consumption and an accompanying 20.88% cost reduction. The same analysis was applied to other demonstration days where PLS was used from June 24 to June 39, 2014. Figure 54 and Table 18 show the ideal energy use for each demonstration day compared to the baseline.

Figure 54 shows the PCM module would achieve modest reductions: on average 6.18% daily ECU energy consumption, and 4.19% daily building total energy consumption. Before discussing how these reductions translate into cost savings, it should be noted that Tyndall AFB, FL is on a Real Time (RT) pricing plan, where the hourly cost of electricity ($/kWh) varies. After examining several months of power bills, the hourly electricity prices look very much like a Time of Use (TOU) plan, where the cost of electricity is substantially higher during peak hours (1:00:00PM to

7:00:00PM) than for the rest of the day. This cost increase during peak hours does not appear to occur on weekends. In other words, the cost benefit of shifting ECU operation to off peak hours on the weekend is lost due to minimal change in the hourly price of electricity.

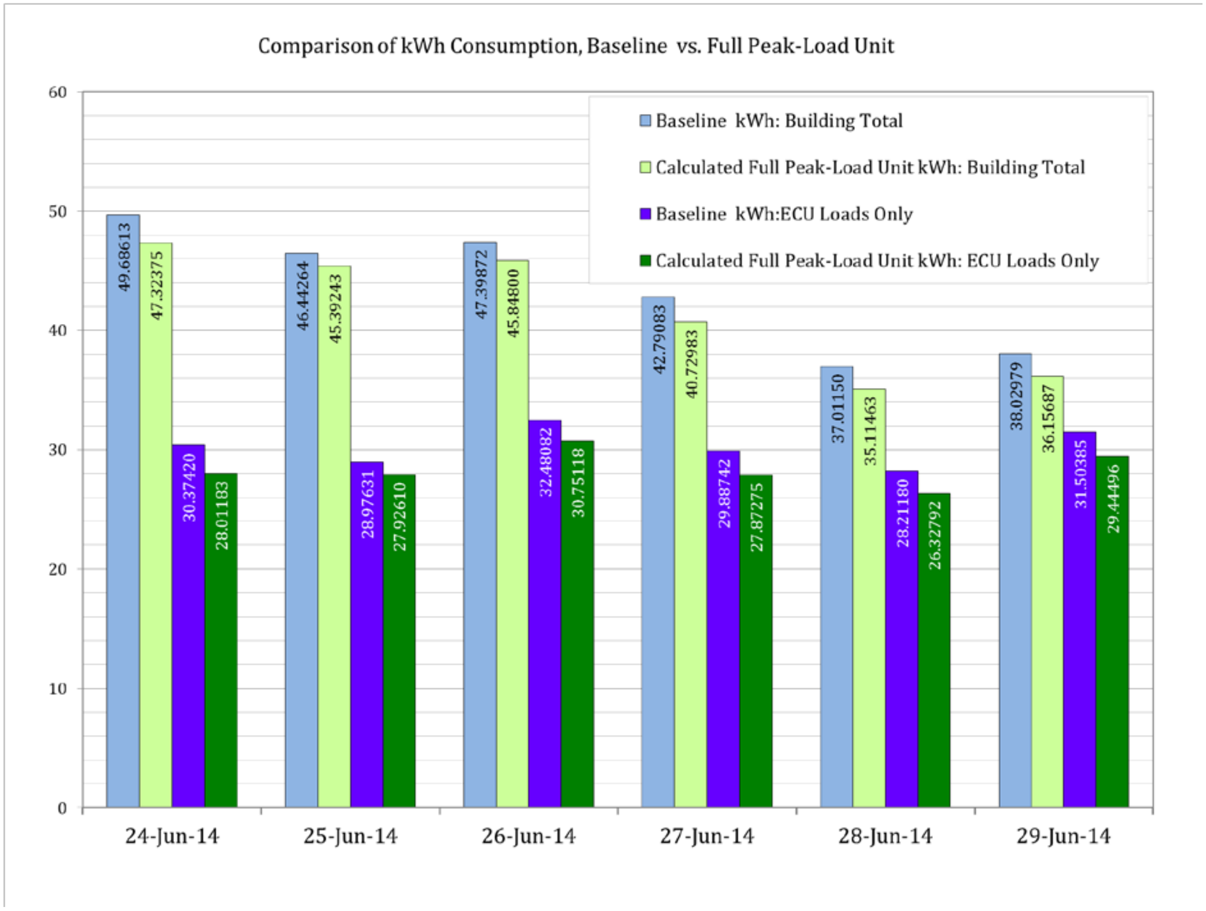


Figure 54: Daily Energy Consumption for Ideal PLS Operation

Table 18: Energy Reduction for Ideal PLS Operation

Percentge Reduction: Building Total	4.75%	2.26%	3.27%	4.82%	5.13%	4.92%	4.19%
Baseline kWh: Building Total	49.6861	46.4426	47.3987	42.7908	37.0115	38.0298	43.5599
Calculated Full Peak-Load Unit kWh: Building Total	47.3238	45.3924	45.8480	40.7298	35.1146	36.1569	41.7609
Percentge Reduction: HVAC Only	7.78%	3.62%	5.33%	6.74%	6.68%	6.91%	6.18%
Baseline kWh: HVAC Loads Only	30.3742	28.9763	32.4808	29.8874	28.2118	31.5038	30.2391
Calculated Full Peak-Load Unit kWh: HVAC Only	28.0118	27.9261	30.7512	27.8728	26.3279	29.4450	28.3891
	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Average
	24-Jun-14	25-Jun-14	26-Jun-14	27-Jun-14	28-Jun-14	29-Jun-14	

Table 19 shows the accompanying cost reductions for the ideal cases discussed above.

Table 19: Cost Reductions for Ideal Peak Load Shaving

Percentage Cost Reduction: Building Total	13.89%	12.55%	14.28%	15.70%	7.14%	7.50%	11.84%
Baseline Daily $ Cost: Building Total	$ 4.39	$ 4.23	$ 4.27	$ 4.04	$ 2.78	$ 2.87	$ 3.76
Calculated Full Peak-Load $ Cost: Building Total	$ 3.78	$ 3.70	$ 3.66	$ 3.40	$ 2.58	$ 2.65	$ 3.30
Percentage Cost Reduction: HVAC Only	21.96%	19.53%	20.88%	22.39%	9.28%	10.17%	17.37%
Baseline Daily $ Cost: HVAC Only	$ 2.78	$ 2.72	$ 3.06	$ 2.81	$ 2.13	$ 2.21	$ 2.62
Calculated Full Peak-Load $ Cost: HVAC Only	$ 2.17	$ 2.19	$ 2.43	$ 2.18	$ 1.93	$ 1.99	$ 2.15
	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Average
	24-Jun-14	25-Jun-14	26-Jun-14	27-Jun-14	28-Jun-14	29-Jun-14	

The average ECU cost reduction in Table 19 is 21.19% on weekdays and 9.72% savings on weekends. For the building as a whole, the average cost reduction is 13.57% on weekdays and 7.32% on weekends. Therefore, for a given week, we can expect approximately a 17.37% reduction in the cost of ECU energy and an 11.84% cost reduction in total building energy.

The next challenge was to quantify the energy and cost savings over time. Given the huge volume of data (data capture once per second), it was impractical to calculate energy and cost savings per day for an extended period. Table 21 represents a consolidation of data from 1 May through 31 Aug 2014 to a representative average day for the entire 4-month hot-weather period. This day was constructed by averaging the weather conditions for each hour for the entire summer period. Next, the hourly baseline energy consumption was established for the representative day. During the PLS demonstration, the PCM-filled ceiling coils were also present in the building. Therefore, to determine the effect of the PLS system on ECU energy consumption, the baseline for the representative day should be the anticipated hourly energy use with the ceiling coils in place. This baseline was established using data from July 17 to September 31, where the PCM-filled ceiling coils were in place and the PLS unit was not used. A linear regression was used to relate the hourly ECU energy use to weather parameters; Sol-air temperature (section 5.2.2) and ambient humidity ratio. This regression showed a high R-squared value of greater than 0.9. The coefficients and regression statistics are shown in Table 20.

Table 20: Linear Regression: Hourly ECU Energy Use as a Function of Sol-air Temperature and Humidity Ratio

Coefficients			Regression Statistics	
Intercept	-15.77987835		Multiple R	0.952130358
T_{sol} (°F)	0.02785564		R Square	0.906552218
H_{ramb}	765.417306		Adjusted R Square	0.897652429

This regression was used to produce the ECU energy consumption (kWh) for each hour of the representative day using that hour's Sol-air temperature and humidity ratio. This formed the baseline used in the lower half of Table 21. The baseline was then modified during charging and discharging hours using the adjustments outlined above and in section 6.2: Ideal PLS operation as shown in the upper half of Table 21. The hourly price of electricity was determined by averaging

the price of electricity at each hour for a week. This ensured the results accounted for decreased cost savings on weekends.

Table 21: Representative Day

		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non ECU kWh	24-Hour Non-HVAC Total Energy Cost	HVAC Total kWh	24-Hour ECU Energy Cost		
1 May - 31 Aug 2014 Representative Day Calculated Peak Load Shaving	Off-Peak	0:00-01:00	1.568024496	$ 0.113287530	0.723491504	$ 0.052271228	0.844532992	$ 0.061016302	$ 0.07225	
		01:00-02:00	1.478842417	$ 0.105610475	0.722739184	$ 0.051613903	0.756103233	$ 0.053996572	$ 0.07141	
		02:00-03:00	1.462372223	$ 0.103817982	0.712140624	$ 0.050556898	0.750231599	$ 0.053261085	$ 0.07099	
		03:00-04:00	3.811032326	$ 0.267420138	0.713692167	$ 0.050079779	3.097340159	$ 0.217340359	$ 0.07017	Charging
		04:00-05:00	3.452648197	$0.241828412	0.707726719	$0.049570190	2.744921478	$0.192258222	$ 0.07004	Charging Half Hour + Catch Up
		05:00-06:00	1.158342317	$ 0.081896457	0.700321125	$ 0.049513704	0.458021192	$ 0.032382753	$ 0.07070	
		06:00-07:00	1.068534679	$ 0.076171258	0.637800911	$ 0.045466093	0.430733769	$ 0.030705164	$ 0.07129	
		07:00-08:00	1.377050388	$ 0.100050580	0.624601914	$ 0.045380898	0.752448474	$ 0.054669681	$ 0.07266	
		08:00-09:00	1.764901286	$ 0.129463073	0.620256279	$ 0.045498456	1.144645007	$ 0.083964617	$ 0.07335	
		09:00-10:00	1.959366802	$ 0.145642533	0.626031369	$ 0.046533806	1.333335432	$ 0.099108727	$ 0.07433	
		10:00-11:00	2.738643499	$ 0.213148623	1.239907992	$ 0.096502039	1.498735506	$ 0.116646584	$ 0.07783	
		11:00-12:00	3.087982495	$ 0.244647619	1.502913558	$ 0.119069400	1.585068937	$ 0.125578219	$ 0.07923	
	Peak	12:00-13:00	0.966804384	$ 0.108638428	0.616002758	$ 0.069219350	0.350801626	$ 0.039419078	$ 0.11237	Discharge
		13:00-14:00	0.966604721	$ 0.112590118	0.615803095	$ 0.071728744	0.350801626	$ 0.040861373	$ 0.11648	
		14:00-15:00	0.977407776	$ 0.113497987	0.626606149	$ 0.072762401	0.350801626	$ 0.040735586	$ 0.11612	
		15:00-16:00	0.972185818	$ 0.112666614	0.621384191	$ 0.072012214	0.350801626	$ 0.040654400	$ 0.11589	
		16:00-17:00	0.974218623	$ 0.110597473	0.623416996	$ 0.070772969	0.350801626	$ 0.039824504	$ 0.11352	
		17:00-18:00	0.988134922	$ 0.107305806	0.637333295	$ 0.069210754	0.350801626	$ 0.038095052	$ 0.10859	
	Off-Peak	18:00-19:00	3.986899488	$ 0.312231186	0.636296380	$ 0.049831097	3.350603108	$ 0.262400089	$ 0.07831	Catch up
		19:00-20:00	1.702623111	$ 0.132875140	0.690733427	$ 0.053905823	1.011889685	$ 0.078969317	$ 0.07804	
		20:00-21:00	1.687672584	$ 0.127706184	0.716467845	$ 0.054215122	0.971204739	$ 0.073491063	$ 0.07567	
		21:00-22:00	1.692202900	$ 0.126243171	0.719077210	$ 0.053645214	0.973125690	$ 0.072597957	$ 0.07460	
		22:00-23:00	1.670486658	$ 0.122690086	0.720418749	$ 0.052911670	0.950067909	$ 0.069778416	$ 0.07345	
		23:00-24:00	1.592111010	$ 0.116399236	0.711164635	$ 0.051993246	0.880946375	$ 0.064405989	$ 0.07311	
		24-Hour Total	43.11	$ 3.43	17.47	$ 1.44	25.64	$ 1.98		
% Power Reduction			2.90%		0.00%		4.78%			
	% Cost Reduction			11.15%		0.00%		17.83%		

		Hour Range	Total kWh per hour	24-Hour Total Energy Cost	Non ECU kWh	24-Hour Non-HVAC Total Energy Cost	ECU Total kWh	24-Hour ECU Energy Cost	Graduated Time-of-Use Cost per kWh
1 May - 31 Aug 2014 Representative Day Baseline Data	Off-Peak	0:00-01:00	1.568024496	$ 0.113287530	0.723491504	$ 0.052271228	0.844532992	$ 0.061016302	$ 0.07225
		01:00-02:00	1.478842417	$ 0.105610475	0.722739184	$ 0.051613903	0.756103233	$ 0.053996572	$ 0.07141
		02:00-03:00	1.462372223	$ 0.103817982	0.712140624	$ 0.050556898	0.750231599	$ 0.053261085	$ 0.07099
		03:00-04:00	1.365022479	$ 0.095783627	0.713692167	$ 0.050079779	0.651330312	$ 0.045703848	$ 0.07017
		04:00-05:00	1.260947438	$ 0.088318560	0.707726719	$ 0.049570190	0.553220719	$ 0.038748369	$ 0.07004
		05:00-06:00	1.158342317	$ 0.081896457	0.700321125	$ 0.049513704	0.458021192	$ 0.032382753	$ 0.07070
		06:00-07:00	1.068534679	$ 0.076171258	0.637800911	$ 0.045466093	0.430733769	$ 0.030705164	$ 0.07129
		07:00-08:00	1.377050388	$ 0.100050580	0.624601914	$ 0.045380898	0.752448474	$ 0.054669681	$ 0.07266
		08:00-09:00	1.764901286	$ 0.129463073	0.620256279	$ 0.045498456	1.144645007	$ 0.083964617	$ 0.07335
		09:00-10:00	1.959366802	$ 0.145642533	0.626031369	$ 0.046533806	1.333335432	$ 0.099108727	$ 0.07433
		10:00-11:00	2.738643499	$ 0.213148623	1.239907992	$ 0.096502039	1.498735506	$ 0.116646584	$ 0.07783
		11:00-12:00	3.087982495	$ 0.244647619	1.502913558	$ 0.119069400	1.585068937	$ 0.125578219	$ 0.07923
	Peak	12:00-13:00	2.313212291	$ 0.259932361	0.616002758	$ 0.069219350	1.697209533	$ 0.190713011	$ 0.11237
		13:00-14:00	2.485077309	$ 0.289461805	0.615803095	$ 0.071728744	1.869274215	$ 0.217733061	$ 0.11648
		14:00-15:00	2.536814881	$ 0.294578568	0.626606149	$ 0.072762401	1.910208732	$ 0.221816167	$ 0.11612
		15:00-16:00	2.369925428	$ 0.274650658	0.621384191	$ 0.072012214	1.748541237	$ 0.202638444	$ 0.11589
		16:00-17:00	2.265967748	$ 0.257242370	0.623416996	$ 0.070772969	1.642550752	$ 0.186469401	$ 0.11352
		17:00-18:00	1.990683889	$ 0.216176895	0.637333295	$ 0.069210754	1.353350594	$ 0.146966141	$ 0.10859
	Off-Peak	18:00-19:00	1.796596895	$ 0.140699203	0.63629638	$ 0.049831097	1.160300515	$ 0.090868106	$ 0.07831
		19:00-20:00	1.702623111	$ 0.132875140	0.690733427	$ 0.053905823	1.011889685	$ 0.078969317	$ 0.07804
		20:00-21:00	1.687672584	$ 0.127706184	0.716467845	$ 0.054215122	0.971204739	$ 0.073491063	$ 0.07567
		21:00-22:00	1.692202900	$ 0.126243171	0.71907721	$ 0.053645214	0.973125690	$ 0.072597957	$ 0.07460
		22:00-23:00	1.670486658	$ 0.122690086	0.720418749	$ 0.052911670	0.950067909	$ 0.069778416	$ 0.07345
		23:00-24:00	1.592111010	$ 0.116399236	0.711164635	$ 0.051993246	0.880946375	$ 0.064405989	$ 0.07311
		24-Hour Total	44.39	$ 3.86	17.47	$ 1.44	26.93	$ 2.41	

The energy and cost savings for the representative day compared to the baseline are summarized in Figure 55.

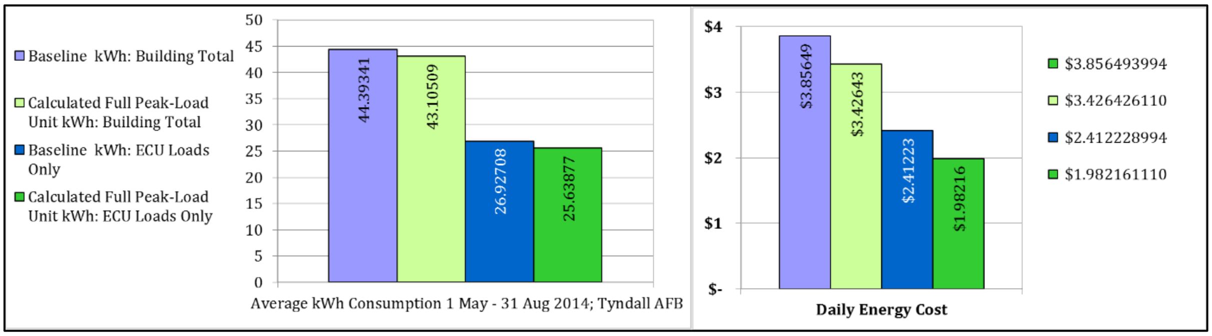


Figure 55: Energy and Cost Savings for Representative Day

These data represent a 4.78% reduction in ECU energy consumption and 17.83% reduction in ECU energy cost, which translates to 1.2883 kWh and $0.430 per day. Multiplying these values by the estimated 165 days per year when the PLS cost/benefit ratio is expected to be above the beneficial “balance point” yields an estimated annual energy savings of 212.5695 kWh for a cost avoidance of $ 70.95.

Higher Energy Density Materials: As advances in PCM technology and manufacturing methods are made, the peak load shaving PCM unit will become smaller, lighter and less expensive. In the immediate future, the demonstration unit can be improved by replacing Quartek Q18 with PCM 11 from Kaplan Energy. At 320 kJ/kg heat storage capacity, PCM 11 has nearly double the heat storage capacity of the Quartek Q18 (207 kJ/kg) which was used in the demonstration prototype. Table 22 below compares the energy density of the two materials:

Table 22: Energy Density Comparison

	QuarTek Q18	99% Hexadecane	Kaplan PCM 11
Latent Heat (kJ/kg)	207	230	320
Density (kg/m^3)	815	770	773
Energy Density (kJ/m^3)	168,705	177,100	247,360

As shown in the table, the energy density of hexadecane is 18% higher than that of Q18, which corresponds to an 18% reduction in the footprint of the PCM heat exchanger and a smaller pressure drop. Even better, Kaplan PCM 11 shows a 46.6% higher energy density and reduction in footprint.

Also important is the weight reduction that can be achieved. For example, it was determined that 85,500 kJ (80,975 BTU) of heat storage was required to support the 6 hour peak load for the demonstration building. With Q18, that corresponds to 413 kg (908.7 lbs) of material. However with hexadecane, only 371.7 kg (819.5 lbs) is required to store the same amount of heat, yielding a 23.9% weight reduction. Similarly, only 267.2 kg (589 lbs) of Kaplan PCM 11 are required, yielding a 35.3% weight reduction.

After conducting market research, ARA determined that hexadecane can be procured for $1.70/lb. in bulk orders. ARA is still talking to vendors to find competitive prices and materials for Kaplan

PCM 11. However, future advances in PCM technology will continue to reduce the footprint, weight, and cost of the PCM heat exchanger, which will ultimately be the key to achieving short payback periods allowing the technology to be commercialized.

Locales with large fluctuations in day/night temperature and/or hourly energy costs: With respect to the technology's application in other climates, the equations used in the analysis are only accurate for the range of weather used to generate the formulas. Therefore, they cannot be used in regions with ranges of ambient temperature and humidity that differ significantly from the demonstration. However, cities with large fluctuations in hourly electricity rates and ambient temperature are good candidates to test the technology.

For example, Pacific Gas and Electric (PG&E) energy pricing system in summer includes peak hours cost of $0.566/kWh from 12pm-6pm, partial peak hours cost of $0.263/kWh from 8:30am-12pm and 6pm-9:30pm, and off-peak hours cost of $0.148/kWh.

Figure 56 summarizes two hypothetical BLCC cases for Sacramento, CA. The column on the left shows a potentially feasible payback using the ECU system to regenerate the PCM during off-peak hours. The right side column shows more favorable payback by using night-time air to regenerate the system. The high cost of energy and climate indicate that Sacramento, CA may present a good opportunity for the technology. However testing and analysis in this climate is needed to accurately project energy savings.

Sacramento, CA	
HVAC Closed Loop Off-Peak Recharging	**Night-Time Air Recharging**
Savings-to-Investment Ratio (SIR) = 1.13	Savings-to-Investment Ratio (SIR) = 1.81
Adjusted Internal Rate of Return = 2.92%	Adjusted Internal Rate of Return = 4.52%
Simple Payback occurs in year 22	Simple Payback occurs in year 14
Discounted Payback occurs in year 30	Discounted Payback occurs in year 16

Figure 56: BLCC Summaries for Sacramento, CA

APPENDIX C: PCM Material Safety Data Sheet (MSDS)

Q18 PCM Material Safety Data Sheet

Material Safety Data Sheet

PRODUCT NAME: BioPCM- Q18

COMPOSITION / INGREDIENTS

Chemical Formula: A proprietary blend of fatty acids, fatty alcohols and fatty esters – all are KOSHER food grade materials

HAZARD IDENTIFICATION

TRADE NAME	BioPCM-Q18
DATE:	May 15, 2012
Address:	QuarTeK Corporation 4180 Piedmont Parkway Greensboro, NC 27410
TELEPHONE:	(336) 316-0088

ENVIRONMENTAL HAZARDS: None identified
HUMAN HEALTH HAZARDS EFFECT AND SYMPTOMS:
INGESTION: May cause slight irritation to gastrointestinal tract
INHALATION: No harmful effects expected at ambient temperature. Mist/vapors could be an irritant to pulmonary tract.
SKIN CONTACT: Slight irritant EYE CONTACT: Mild transient irritant

FIRST AID MEASURES

INGESTION: Consult a doctor immediately. Drink plenty of water. Do not give anything by mouth to an unconscious person.
INHALATION: Move to fresh air immediately. In case of breathing difficulty, try artificial respiration. Get medical attention ASAP.
SKIN: Wash material off the skin with copious amounts of soap and water. If redness or itching persists, seek medical attention.
EYE: Rinse eyes with water for at least 15 minutes. If redness or itching persists, seek medical attention.

FIRE FIGHTING MEASURES / FIRE HAZARDS

ACCIDENTAL RELEASE MEASURES

PERSONAL PRECAUTIONS: No stringent special precaution. Take normal industry standard measures.
ENVIRONMENTAL PRECAUTIONS: In case of spillage, take up with sand/soil and disposed the same. Minimize entry into drains & ground water.
METHOD OF CLEANINBG UP: Collect in dry earth, sand. Transfer to container for disposal. Flush area with water.

HANDLING

HANDLING: Follow good hygiene and safety procedures. Avoid any direct contact. Wash with soap and water after handling. Keep away from heat, strong acids and oxidizing agents.

EXPOSURE CONTROL AND PERSONAL PROTECTION

RESPIRATORY SYSTEM PROTECTION: None required when adequate ventilation is available at ambient temperature. In the presence of mist/vapor, use self-contained NIOSH/MSH approved respirator.
SKIN/BODY PROTECTION: Uniform, apron and rubber boots
HAND PROTECTION: Rubber gloves
EYE PROTECTION: safety goggles, face mask

PHYSICAL AND CHEMICALS PROPERTIES

APPEARANCE @ 18°C: White solid
PHYSICAL STATE > 20°C: Colorless Liquid
COLOR: White in solid form / Colorless in liquid form
ODOR: Practically no odor
BOILING RANGE, °C: 305 – 330

VAPOUR DENSITY (AIR=1):	
VAPOUR PRESSURE, mm of Hg:	<10 mm @ 22°C
FLASH POINT:	Approx. 175°C, PMCC
AUTO IGNITION TEMP.:	Not Available
EXPLOSION LIMIT:	
UPPER:	Not Available
LOWER	Not Available
AVERAGE MOLECULAR WT.:	238 – 249

MELTING RANGE, °C: 30-35
SOLUBILITY IN WATER: Insoluble in water
SOLUBILITY OIL & SOLVENTS: Not Available RELATIVE DENSITY: 0.815 @ 60°C

STABILITY AND REACTIVITY

CHEMICAL STABILITY: Stable under normal operating conditions
CONDITIONS TO AVOID: Sources of heat, ignition and flame
MATERIALS TO AVOID: Strong acids and oxidizing agents
HAZARDOUS POLYMERIZATION PRODUCTS: None HAZARDOUS
DECOMPOSTION PRODUCTS: Carbon monoxide and carbon dioxide

TOXICOLOGY INFORMATION

ACUTE TOXICITY ORAL (LD50) (RAT): >20.5 g/Kg
DERMAL (LD50) (RABBIT): Not Available
INHALATION (LC50): Not Available
SKIN IRRITATION: No irritation in humans observed in repeated insult test done using undiluted product.
EYE IRRITATION: Mild transient irritation. Mild irritation observed in rabbits @ 500mg dosage level of undiluted product
SENSITIZATION: Not Available
CHRONIC TOXICITY: Not Available
CARCINOGENICITY: Not Available

MODE OF DISPOSAL

METHODS OF DISPOSAL: Disposal methods to be in accordance with local, federal and state environmental regulations.

REGULATORY INFORMATION

According to available data, fatty acid is not a dangerous chemical. However, one should observe the usual precautionary measures for dealing with chemicals according to local, state and federal regulations & requirements.

This product is very easily biodegradable (99%) and does not cause difficulties in waste water treatment plants. Being water insoluble and lighter than water, large amounts of contamination can be separated using typical standard oil/fats separators.

PT18 Material Safety Data Sheet

Renewable Phase Change Technology

Material Safety Data Sheet

Material Name: PureTemp 18

* * * Section 1 - Chemical Product and Company Identification * * *

Manufacturer Information

Entropy Solutions Inc.
151 Cheshire Lane
Suite 400
Plymouth, MN 55441

Phone: 952-941-0306

* * * Section 2 - Hazards Identification * * *

Emergency Overview

May cause eye, skin and gastrointestinal irritation.

Potential Health Effects: Eyes

May cause eye irritation.

Potential Health Effects: Skin

May cause skin irritation.

Potential Health Effects: Ingestion

Not considered a likely route of exposure under normal product use conditions. May cause gastrointestinal irritation if swallowed.

Potential Health Effects: Inhalation

None anticipated under normal product use conditions.

HMIS Ratings: Health: 1 **Fire:** 0 **HMIS Reactivity** 0

Hazard Scale: 0 = Minimal 1 = Slight 2 = Moderate 3 = Serious 4 = Severe * = Chronic hazard

* * * Section 3 - Composition / Information on Ingredients * * *

CAS #	Component
Trade Secret	Proprietary

* * * Section 4 - First Aid Measures * * *

First Aid: Eyes

In case of contact, immediately flush eyes with large amounts of water, continuing to flush for 15 minutes.

First Aid: Skin

For skin contact, wash immediately with soap and water. If irritation persists, get medical attention.

First Aid: Ingestion

If the material is swallowed, get immediate medical attention or advice -- Do not induce vomiting.

First Aid: Inhalation

If the affected person is not breathing, apply artificial respiration.

* * * Section 5 - Fire Fighting Measures * * *

General Fire Hazards

See Section 9 for Flammability Properties.

None

Hazardous Combustion Products

Carbon monoxide with incomplete combustion.

Extinguishing Media

Small fires: CO_2 or dry chemical

Large fires: foam

Fire Fighting Equipment/Instructions

Firefighters should wear full protective gear.

NFPA Ratings: Health: 1 **Fire:** 0 **Reactivity:** 0

Hazard Scale: 0 = Minimal 1 = Slight 2 = Moderate 3 = Serious 4 = Severe

Material Safety Data Sheet

Material Name: PureTemp 18

*** Section 6 - Accidental Release Measures ***

Containment Procedures

Stop the flow of material, if this is without risk.

Clean-Up Procedures

Ventilate area and eliminate all ignition sources. Contain spill. Absorb or cover with dry earth, sand or other non-combustible material and transfer to containers for disposal. Use clean non-sparking tools to collect absorbed material.

Evacuation Procedures

Isolate area. Keep unnecessary personnel away.

Special Procedures

Dike flow of spilled material using soil or sandbags to minimize contamination of drains, surface and ground waters.

*** Section 7 - Handling and Storage ***

Handling Procedures

Avoid contact with skin and eyes. Wash thoroughly after handling.

Storage Procedures

Keep the container tightly closed and in a cool, well-ventilated place.

*** Section 8 - Exposure Controls / Personal Protection ***

A: Component Exposure Limits

ACGIH, OSHA, and NIOSH have not developed exposure limits for any of this product's components.

Engineering Controls

Use general ventilation.

PERSONAL PROTECTIVE EQUIPMENT

Personal Protective Equipment: Eyes/Face

Goggles or face shield with goggles, dependent upon potential exposure

Personal Protective Equipment: Skin

Use impervious gloves.

Personal Protective Equipment: Respiratory

Not normally needed.

Personal Protective Equipment: General

Eye wash fountain and emergency showers are recommended.

*** Section 9 - Physical & Chemical Properties ***

Appearance:	Clear liquid. White solid.	**Odor:**	Faint to light musty
Physical State:	Liquid	**pH:**	ND
Vapor Pressure:	>5 mm Hg @ 25°C (77°F)	**Vapor Density:**	0.88 @ 25°C (77°F)
Boiling Point:	>315°C (600°F)	**Melting Point:**	18°C (64.4°F)
Solubility (H2O):	Negligible	**Specific Gravity:**	0.81 @25°C (77°F)
Evaporation Rate:	NA	**VOC:**	ND
Octanol/H2O Coeff.:	ND	**Flash Point:**	141°C (286°F)
Flash Point Method:	PMCC	**Upper Flammability Limit (UFL):**	ND
Lower Flammability Limit (LFL):	ND	**Burning Rate:**	ND
Auto Ignition:	ND		

*** Section 10 - Chemical Stability & Reactivity Information ***

Chemical Stability

This is a stable material.

Chemical Stability: Conditions to Avoid

None

Incompatibility

Avoid oxidizing agents.

Material Safety Data Sheet

Material Name: PureTemp 18

Hazardous Decomposition
Carbon monoxide with incomplete combustion.

Possibility of Hazardous Reactions
Will not occur.

* * * Section 11 - Toxicological Information * * *

Acute Dose Effects

A: General Product Information
No information available for the product.

B: Component Analysis - LD50/LC50
No LD50/LC50's are available for this product's components.

Carcinogenicity

A: General Product Information
No information available for the product.

B: Component Carcinogenicity
None of this product's components are listed by ACGIH, IARC, OSHA, NIOSH, or NTP.

* * * Section 12 - Ecological Information * * *

Ecotoxicity

A: General Product Information
No information available for the product.

B: Component Analysis - Ecotoxicity - Aquatic Toxicity

Proprietary (Trade Secret)

Test & Species		Conditions
96 Hr LC50 Brachydanio rerio	1700 mg/L [semi-static]	
96 Hr LC50 Brachydanio rerio	1700 mg/L	

* * * Section 13 - Disposal Considerations * * *

US EPA Waste Number & Descriptions

Component Waste Numbers
No EPA Waste Numbers are applicable for this product's components.

Disposal Instructions
All wastes must be handled in accordance with local, state and federal regulations.
See Section 7 for Handling Procedures. See Section 8 for Personal Protective Equipment recommendations.

* * * Section 14 - Transportation Information * * *

US DOT Information
Shipping Name: Not Regulated

* * * Section 15 - Regulatory Information * * *

US Federal Regulations

Component Analysis
None of this products components are listed under SARA Section 302 (40 CFR 355 Appendix A), SARA Section 313 (40 CFR 372.65), or CERCLA (40 CFR 302.4).

State Regulations

Component Analysis - State
None of this product's components are listed on the state lists from CA, MA, MN, NJ, PA, or RI.

Component Analysis - WHMIS IDL
No components are listed in the WHMIS IDL.

Additional Regulatory Information

Material Safety Data Sheet

Material Name: PureTemp 18

Component Analysis - Inventory

Component	CAS #	TSCA	CAN	EEC
Proprietary	Trade Secret	Yes	DSL	EINECS

* * * Section 16 - Other Information * * *

Other Information

The information herein is presented in good faith and believed to be accurate as of the effective date given. However, no warranty, expressed or implied, is given. It is the buyer's responsibility to ensure that its activities comply with Federal, State or provincial, and local laws.

Key/Legend

EPA = Environmental Protection Agency; TSCA = Toxic Substance Control Act; ACGIH = American Conference of Governmental Industrial Hygienists; IARC = International Agency for Research on Cancer; NIOSH = National Institute for Occupational Safety and Health; NTP = National Toxicology Program; OSHA = Occupational Safety and Health Administration., NJTSR = New Jersey Trade Secret Registry.

End of Sheet

PCM – PT18 Technical Data Sheet

PureTemp® Thermal Energy Storage Materials

PureTemp thermal energy storage materials offer new levels of performance in storing or releasing large quantities of thermal energy at any given temperature. Our proprietary formulations and patented manufacturing processes yield superior quality biobased phase change materials at cost effective prices.

Some key properties:

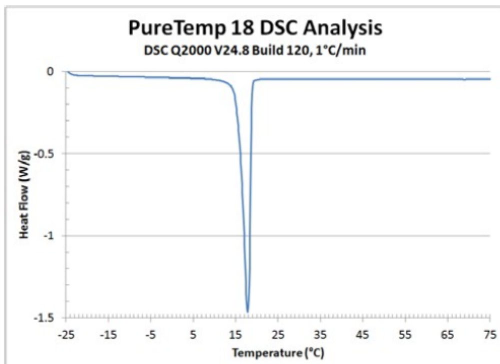
- Thermal energy storage capacities which average 200 J/g
- Over 200 unique, engineered phase change transition temperatures between -40 ˚C and 151 ˚C
- Consistent, repeatable performance over thousands of thermal (melt/solidify) cycles
- 100% renewable and readily biodegradable – produced from agricultural sources, not petroleum

PureTemp 18 Technical Information

PureTemp 18 is a USDA Certified Biobased product

Appearance	Clear liquid, waxy solid
Melting point	18 °C
Heat storage capacity	192 J/g
Thermal conductivity (liquid)	0.15 W/m°C
Thermal conductivity (solid)	0.25 W/m°C
Density (liquid)	0.86 g/ml
Density (solid)	0.95 g/ml
Specific heat (liquid)	1.74 J/g˚C
Specific heat (solid)	1.47 J/g˚C

Typical physical properties are listed in the table above.



Thermal Cycle Stability

A thermal cycle stability study was performed on PureTemp 18 in which samples underwent a series of freeze and thaw cycles. The two-year study completed 10,000 thermal cycles, with performance analyses performed on the samples at various time points. The study for PureTemp 18 found that:

- The average latent heat for PureTemp 18, over the course of 10,000 cycles, passes the product specification.
- PureTemp 18 maintained a peak melting point of 19.1 ± 0.3 °C.

PureTemp 18 is stable through 10,000 thermal cycles, which is approximately 27.4 years of continuous daily usage.

Entropy Solutions, Inc.
151 Cheshire Lane N. Suite 400, Plymouth, MN 55441
Tel: +1-952-941-0306
Inquiry: www.puretemp.com/contact
Website: www.puretemp.com

USDA CERTIFIED BIOBASED PRODUCT
PRODUCT 100%

APPENDIX D: Sensor Calibration

Sensors were calibrated using procedures specific to the sensor type. The duct mount station (measuring volumetric flow rate) was not calibrated, as it was calibrated by the manufacturer. The thermocouple probes and the LabView chassis were also not calibrated for the same reason. ARA calibrated the thermocouple wires connecting the probes to the LabView chassis using a Fluke 714 Thermocouple Calibrator. The procedure was as follows:

1) Disconnect thermocouple probe from thermocouple wire
2) Connect Fluke 714 thermocouple calibrator to thermocouple wire
3) Use Fluke 714 thermocouple calibrator to send 50F temperature signal through thermocouple wire to LabView chassis
4) Read the temperature displayed by LabView
5) Record the difference between the value displayed by LabView and the signal from the Fluke 714 thermocouple calibrator
6) Repeat steps 3-5 for 100F and 150F signals

Table 23 below shows the values displayed by LabView for the 50F, 100F, and 150F signals provided by the Fluke 714 thermocouple calibrator.

Table 23: Thermocouple Calibration Using Fluke 714 Thermocouple Calibrator

Thermocouple	Temp 50	Temp 100	Temp 150	Thermocouple	Temp 50	Temp 100	Temp 150
AirHandTC-R				MainTC-NC-5	50.152	100.4444	150.3737
AirHandTC-S	49.5823	99.8138	149.8653	MainTC-NC-6	49.6628	99.9673	149.9984
AirHandTC-PCM				MainTC-C-1	49.2895	99.4242	149.3831
MechTC	50.1997	100.4253	150.4623	MainTC-C-2	48.9395	99.0991	149.1871
LadyTC-1	49.5217	99.7198	149.7227	MainTC-C-3	48.8843	99.0706	149.0872
LadyTC-2	49.6357	99.8167	149.7593	MainTC-C-4	49.4927	99.6894	149.7283
MensTC-1	49.6199	99.7874	149.8793	MainTC-C-5	49.6234	99.8213	149.6197
MensTC-2	49.8106	99.9504	149.8891	MainTC-C-6	49.2936	99.4809	149.4371
MainTC-N-1	49.0355	99.1076	149.1272	MainTC-SC-2	48.9873	99.2216	149.1621
MainTC-N-2	50.2357	100.4356	150.4512	MainTC-SC-3	48.9635	99.1856	149.1892
MainTC-N-3	50.0165	100.1653	150.1011	MainTC-SC-4	49.0266	99.2743	149.2693
MainTC-N-4	49.7942	99.9979	149.8754	MainTC-SC-5	49.1276	99.3821	149.3555
MainTC-N-5	49.5865	99.7728	149.7283	MainTC-SC-6	49.2358	99.4487	149.481
MainTC-N-6	49.5326	99.7259	149.6112	MainTC-S-2	50.6682	100.6931	150.4481
MainTC-NC-1	49.6961	99.8551	149.8888	MainTC-S-3	49.8642	99.9721	149.9636
MainTC-NC-2	49.6871	99.9379	149.8852	MainTC-S-4	49.7487	99.8848	149.9427
MainTC-NC-3	50.7876	100.9572	150.8514	MainTC-S-5	49.6948	99.9072	149.9237
MainTC-NC-4	50.6816	100.8731	150.7493	MainTC-S-6	49.6105	99.8101	149.7421

ARA also calibrated the relative humidity sensors using the calibration kit provided by the manufacturer. For reference, this procedure is outlined by Omega[1]. The results for the relative humidity sensor calibrations are summarized in Table 24.

[1] Relative Humidity Calibration Kit, http://www.omega.com/manuals/manualpdf/M969.pdf.

Table 24: Relative Humidity Sensor Calibration

Humidity Sensor	Time Start	Time End	11 Percent	Time Start	Time End	75 Percent
MechRH						
LadyRH	2:27 PM	3:08 PM	10.42%			
MensRH	2:04 PM	2:25 PM	11.09%			
MainRH-N-2	1:21 PM	2:01 PM	10.85%	2:25 PM	3:25 PM	76.34%
MainRH-NC-4	12:35 PM	1:19 PM	10.24%			
MainRH-C-6	11:05 AM	12:33 PM	10.33%			
MainRH-SC-4	10:18 AM	11:03 AM	10.38%	1:00 PM	1:50 PM	76.10%
MainRH-S-2	9:45 AM	10:45 AM	14.80%	10:45 AM	1:00 PM	75.70%

Power transducers were calibrated using a Fluke 435 Power Quality Analyzer. Once the Fluke 435 was connected, the lights, heat pump, and water heater were used to test the full range of power consumption in the building. In each case, the power transducer measurements in LabView were compared to the measurements from the Fluke 435 Power Quality Analyzer. The different combinations of lights, heat pump operations, and water heater operation along with the corresponding LabView measurements and Fluke 435 measurements are shown in Table 25 and are indicated in the column headings by “VI” and “M” respectively.

Table 25: Power Transducer Calibration

Power Calibration											
Location	Total Gym (VI)	Total Gym (M)	Air Handler (VI)	Air Handler (M)	Cond. E (VI)	Cond. E (M)	Cond. W (VI)	Cond W (M)	VI Correction	PF	kVa
Total Gym	1150	470	200		85		115		-770	0.65	520
Total Gym /Lights	3000	2320	200		95		140			0.95	2340
Total Gym/ Airhandler	1600	870	700		85		120			0.6	1330
Total Gym/ Airhandler / Lights	3500	2810	670		70		100			0.9	3080
Total Gym/ Airhandler/ Condensor West	4500	3600	700		70		3100			0.81	4350
Total Gym/ Airhandler/ Condensor West/Lights	6300	5500	690		90		3100			0.89	6080
Total Gym/ Water Heater	4100	3500	230		80		100			0.88	3920
Total Gym/ Water Heater/ Airhandler/ Condensor W/Lights	8500	7520	670		60		3100			0.91	8320
	9300	8430	690		110		3100			0.92	9075
Air Handler	1600		670	480	80		140		-200	0.45	960
Airhandler/ Lights	3700		680	480	70		130			0.45	960
Airhandler/ Condensor W	4400		630	480	80		3050			0.45	980
Airhandler/ Lights/ Condenser West	6000		700	480	70		3080			0.45	980
Condeser West	4500		710		37		3080	2700	-380	0.85	3100
Condenser West/ Lights	6300		710		70		3080	2700		0.85	3100
Condenser East					3080	2820			-290	0.85	3220
Condenser East/Lights					3080	2800				0.85	3200
	WH (M) Watts	WH (M) kVA	WHPF								
Water Heater	3100	3580	0.86								
	Start kW	End kW	Start kVa	End kVa	Start PF	End PF	Duration				
Lift Station	2390	2290	2810	2710	0.82	0.8	3 Min				
Notes	Measurements taken using filtered VI on June 6 2011 aprox 1400. Fluke meter readings are highlighted in yellow. Lift Staion and Condenser East measurements were taken June 21 2011 aprox 1400.										

Power Calibration with New Units Operating											
	Total Gym (VI)	Total Gym (M)	Air Handler (VI)	Air Handler (M)			Cond. W (VI)	Cond. W (M)		PF	kVa
Cooling Mode			200	260			2260	2380		0.83	2.8
Heat Pump Mode			200	260			3150	3200		0.4	
Heat Pump plus Heat Strips Mode	17000	16600	12100	11800			3150			0.8	
No lights	3400 (base value for testing)										
womens room lights only	3900										
mens room lights only	3900										
main lights only	4500										
Notes	*water heater was on for entire light test.										
	Measurements were taken using filtered VI on November 18 2011 around 1230. Fluke meter readings are highlighted in yellow.										
	It was decided from previous scaling (June 2011) that the power readings for the new units are within an acceptable range and do not need to be rescaled.										

APPENDIX E: Building 9732 Comfort Level Feedback Log

Comfort Level is rated on a scale 1-5
5 is the highest comfort level: very comfortable, no adjustment required
1 is the lowest comfort level: not comfortable, adjustment is required

	Date	Time	Temperature Comfort Level	Humidity Comfort Level	Comments
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					